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GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

FINAL REPORT

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GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

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FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS-3-13469. This contract involves work similar to that conducted under Contracts NAS-3-9439 and NAS-3-2545. The purpose of this study is to obtain design creep data on refractory metal alloys for use in advanced space power systems. A listing of all reports presented to date on this program is included in Appendix I. Additional work on this program is presently being performed under Contract NAS-3-15554.

The program is administered for TRW Inc. by H. E. Collins, Program Manager; K. D. Sheffler is the Principal Investigator with R. R. Ebert contirbuting to the program. The NASA Technical Manager is Paul E. Moorhead.

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ABSTRACT

Ultrahigh vacuum creep tests have been performed on tungsten, molybdenum, and tantalum alloys to develop design creep data and to evaluate the influence of liquid lithium exposure on the creep resistance of a tantalum alloy. Test conditions were generally selected to provide 1% creep in 1000 to 10,000 hours, with the test temperatures ranging between 1600 and 2900°F (1144K and 1866K). One percent creep life data from a tantalum-base T-111 alloy (Ta-8%W-2%Hf) were analyzed using Manson's recently developed station function method to provide an improved parametric representation of the T-111 data. In addition, the minimum creep rate data from an ASTAR 811C alloy (Ta-8%W-1%Re-.7%Hf-.025%C) were analyzed to determine the stress and temperature dependence of creep rate. Results of this analysis indicated that the activation energy for creep decreased from about 150 Kcal/mole (5130 J/mole) above 2400°F (1589K) to about 110 Kcal/mole (3760 J/mole) below 2000°F (1361K). This temperature range corresponds to the range where the creep mechanism changes from grain boundary sliding to intragranular creep.

SUMMARY

Creep tests were conducted in ultrahigh vacuum on the tantalum-base alloys T-111 (Ta-8%W-2%Hf) and ASTAR 811C (Ta-8%W- 7%Hf-1%Re-.025%C), on the molybdenum alloy TZM (Mo-.5Ti-.1Zr), and on pure vapor deposited tungsten. One percent creep life data for the T-111 alloy were analyzed using Manson's recently developed station function analysis. Results of this analysis are presented in the form of an improved parametric representation for the T-111 1% creep life in the temperature range 2200 to 2400°F (1478 to 1589K) and stress range of 1.5 to 12 ksi. In addition, comparative tests were made to evaluate the influence exposure to liquid lithium on the creep strength of the T-111 alloy. Preliminary results showed little difference between the creep strength of specimens exposed to either lithium or to a 10^{-9} torr vacuum for 1000 hours at 2400°F (1589K), with both exposures providing 1% creep lives which were significantly longer than previously observed for the T-111 alloy tests. Efforts are presently underway to obtain samples from the specific heat used in the exposure program so that pre-exposure tests may be performed.

The effort to characterize the creep strength of ASTAR 811C annealed 1/2 hour at 3600°F (2255K) was essentially completed during this report period, with only a few tests remaining in progress from this series. A new sequence of ASTAR tests on specimens annealed 1 hour at 3000°F (1922K) was initiated and preliminary 1% creep data from this series are reported. These data show that the 3600°F (2255K) heat treatment produces superior creep resistance only at the higher temperatures and lower stresses.

An analysis was made of the creep rate data developed on the ASTAR 811C alloy annealed 1/2 hour at 3600°F (2255K) in order to determine the stress and temperature dependence of the creep rate. Results of this analysis showed that the activation energy for creep changed from approximately 150 Kcal/mole (5130 J/mole) in the 2400°F (1589K) range to about 110 Kcal/Mole (3760 J/mole) below 2000°F (1366K). This corresponds to the temperature range where the creep mechanism in the T-111 alloy appears to change from grain boundary sliding to intragranular deformation. The value observed at the higher temperatures seems high when compared with the activation energy for self diffusion in tantalum, which is on the order of 100-110 Kcal/mole (3420-3760 J/mole).

The second of a series of creep tests on CVD tungsten annealed 100 hours at 3272°F (2073K) was initiated during the current period. Results of this test showed an extrapolated 1% creep life of 13,000 hours at 2912°F (1873K) and 1 ksi (6.9 mN/m^2).

In a continuation of a previous study, the influence of both composition and processing on the creep strength of the molybdenum base alloy TZM was examined. A specially processed disc having a higher than normal carbon content and forged at higher than normal temperatures was found to be significantly stronger than a conventionally forged TZM disc.

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INTRODUCTION

Current design concepts for space electric power systems specify refractory metals and alloys in a variety of areas. Among these is the proposed use of molybdenum-base alloys as turbine components and tantalum-base alloys for tubing and capsule fabrication.

One of the most important properties of these materials in such applications is the long time creep strength at elevated temperature. Since the systems under consideration will operate either in the ultrahigh vacuum of outer space or in environments such as metal vapor or liquid metals where the partial pressure of reactive gasses is extremely low, it is necessary to determine the creep properties of the proposed materials of construction in an ultrahigh vacuum environment in order to generate representative design data. Various refractory alloys are therefore being creep tested in a vacuum environment of $<1 \times 10^{-8}$ torr for times up to 15,000 hours. Materials of current interest are the molybdenum-base alloy TZM, the tantalum-base alloys T-111, and ASTAR 811C, and vapor deposited tungsten.

In addition to the design creep tests which are being conducted in this laboratory, a major effort was initiated during the report period to study the influence of liquid lithium exposure on the creep behavior of T-111 alloy. This problem is an important consideration in space power system design because of the potential operation of the T-111 alloy in contact with the liquid metal in nuclear power systems. The program is a cooperative effort between NASA Lewis, who is procuring and heat treating the test specimens, G.E. Evendale, who is performing the liquid metal exposures, and TRW who is performing the UHV creep testing.

EXPERIMENTAL PROCEDURE

Materials

Processing details and sources of each of the test materials have been summarized previously (1). Chemical analyses of each heat of test material are shown in Table 1.

Only one specimen of TZM alloy is currently on test. This specimen was taken from a specially fabricated, stress-relieved disc of TZM alloy (Heat KDTZM-1175) which had a higher than normal carbon content and which was forged at very high temperatures (3400°F (2144K)) in order to provide an improved carbide dispersion (2), with relatively small grain size.

The tantalum alloys are being evaluated predominately in the form of nominal 0.030" sheet, although a few selected tests have been conducted on T-111 alloy in the form of strip or plate. All of the tantalum materials are being evaluated in the fully recrystallized condition. Typical microstructures for these test materials have been presented previously (1). The standard heat treatment for the T-111 alloy is 1 hour at 3000°F (1922K), while the ASTAR 811C alloy is being studied in two conditions of heat treatment, 1/2 hour at 3600°F (2255K) and 1 hour at 3000°F (1922K).

The T-111 test material for the lithium exposure program was fabricated as 0.020" sheet by the Wah Chang Company, Heat No. 650050. The material was procured and specimens were machined and heat treated at the NASA Lewis Research Center. After machining the specimens were given a duplex heat treatment consisting of 1 hour at 3000°F (1922K) followed by 1 hour at 2400°F (1589K) in a diffusion pumped vacuum chamber. This heat treatment was designed to simulate the standard 3000°F (1922K) anneal followed by a post-weld stress relief which would normally be applied to any fabricated hardware item. After annealing, different specimens were exposed to lithium and to a 10^{-9} torr vacuum for 1000 hours at 1800°F (1255K) and at 2400°F (1589K) by the General Electric Co. at Evendale, Ohio. Specific identity numbers of the specimens to be tested in the UHV creep program are given in Table 2. Another series of specimens similar to those listed in Table 2 are currently being exposed for 5000 hours by General Electric, and these specimens will be included in the creep test program when the exposures are completed. The as-received, post annealed and post exposure oxygen analyses for the 1000 hour specimens are presented in Table 3. These analyses, made at the NASA Lewis Research Center, indicate significant oxygen pick-up during the annealing treatment, followed by a corresponding decrease in oxygen level as a result of both the vacuum and the lithium exposures, with the lithium deoxidation being more severe at both exposure temperatures.

Table 1

Chemical Composition of Alloys Being Evaluated in Creep Program

Material	Weight % W	Re	Mo	Ta	Hf	C	Ti	Zr	PPM N_2	O_2	H_2	Finished Form
TZM (Heat KDTZM-1175)			Bal.			.0350	.61	.130	43	34	9	Forged disc
T-111 (Heat 70616)	8.5			Bal.	2.3	.0044			20	55	6	Nominal 0.030" sheet
(Heat 65079)	8.7			Bal.	2.3	.0030			50	130	4	" "
(Heat 65076)	8.6			Bal.	2.0	.0040			20	100	3	" "
(Heat D-1102)	7.9			Bal.	2.3	.0030			34	20	3	" "
(Heat D-1670)	7.9			Bal.	2.4	.0010			20	72	5	" "
(Heat D-1183)	8.7			Bal.	2.2	.0036			10	25	6	" "
(Heat 650028)	8.3			Bal.	2.1	.0030			12	30	1.9	" "
(Heat 848001)	7.9			Bal.	2.0	.0010			13	21	1	" "
(Heat 650038)	8.6			Bal.	2.0	.0025			20	100	2.8	Nominal 0.600" plate
(Heat 8048)	7.6			Bal.	1.9	.0037			24	34	1.6	Nominal 0.165" strip
(Heat 650050)	7.9			Bal.	1.9	.0022			47	33	1	Nominal 0.020" sheet
ASTAR 811C												
(Heat NASV-20-WS)	7.3	1.0		Bal.	0.86	.0240			20	14		Nominal 0.030" sheet
(Heat VAM-95)	7.6	1.1		Bal.	0.65	.0300			3	4	0.3	" "
(Heat 650056)	8.2	1.2		Bal.	0.9	.0200			14	30	3.5	" "
CVD Tungsten	Bal.					.0029			3	12	2	Nominal .060" sheet

Table 2

T-111 Alkali Metal Exposure Program Specimen Identification Numbers

Vacuum Exposed 1000 Hours at 1800°F (1255k)	Lithium Exposed 1000 Hours at 1800°F (1255K)	Vacuum Exposed 1000 Hours at 2400°F (1589K)	Lithium Exposed 1000 Hours at 2400°F (1589K)
01-14	01-10	04-33	01-1
01-15	01-12	04-36	01-3
01-16	04-25	04-37	04-1
01-17	04-26	04-38	04-2
01-18	04-27	04-39	04-4
04-66	04-29	04-41	04-5
04-69	04-30	04-42	04-7
04-70	04-31	04-43	04-8

Table 3

Influence of Heat Treatment and Liquid Metal Exposure on the Oxygen In T-111, Heat 650050

Condition	Oxygen Analysis, ppm*
As Received	33 (average of 4 analyses)
Annealed 1 hour at 3000°F (1922K) plus 1 hour at 2400°F (1589K)	104 (average of 3 analyses)
Exposed to lithium 1000 hours at 1800°F (1255K)	19
Exposed to 10^{-9} torr 1000 hours at 1800°F (1255K)	33
Exposed to lithium 1000 hours at 2400°F (1589K)	6
Exposed to 10^{-9} torr 1000 hours at 2400°F (1589K)	57

* Analyses performed at NASA Lewis Research Center

The CVD tungsten which is being evaluated on this program was obtained in the form of 4" long by .060" thick sheet-type creep test specimens which were vapor deposited and machined to print by the vendor. Chemical analysis from a typical specimen is presented in Table 1. The specimens were of the duplex type, meaning that the cross section contained approximately 45 mils of a structure typical of the fluoride deposition process, and approximately 15 mils of a structure typical of the chloride deposition process. The annealing treatment for these specimens was 100 hours at 3272°F (2073K).

General Test Procedures

The experimental program is devoted to the generation of design data by creep testing sheet and bar specimens at temperatures and stresses which will provide one half to one percent creep in 2000 to 25,000 hours. Two inch gauge length, button-head bar-type specimens and double shoulder, pin loaded, sheet type specimens were used for testing of plate and sheet type materials. The orientation of the specimen with respect to the working direction is given below:

Material Form	Specimen Axis Parallel to
Disc forging	Radius
Plate	Extruded or rolling direction
Sheet	Rolling direction (except where indicated)

Both the construction and operation of the test chambers and the service instruments in the laboratory have been described in detail in previous reports (Appendix I). The creep test procedure involved initial evacuation of the test chamber to a pressure of less than 5×10^{-10} torr at room temperature, followed by heating of the test specimen at such a rate that the pressure never rose above 1×10^{-6} torr. Pretest heat treatments were performed in situ, and complete thermal equilibrium of the specimen was attained by a two-hour hold at the test temperature prior to load application. The pressure was always below 1×10^{-8} torr during the tests and generally fell into the 10^{-10} torr range as testing proceeded. Specimen extension was determined over a two inch gauge length with an optical extensometer which measured the distance between two scribed reference marks to an accuracy of ±50 microinches.

Specimen temperature was established at the beginning of each test using a W-3%Re - W-25%Re thermocouple. Since thermocouples of all types are subject to a time-dependent change in EMF output under isothermal conditions, the absolute temperature during test was maintained by an optical pyrometer. In practice the specimen was brought to the desired test temperature using a calibrated thermocouple attached to the specimen as a temperature standard. The use of this thermocouple was continued during the temperature stabilization period which lasted 50 to 100 hours. At this time, a new reference was established using an optical pyrometer having the ability to detect a temperature difference of ±1F°, and this reference was used subsequently as the primary temperature standard.

RESULTS AND DISCUSSION

Presentation and discussion of the test results will be divided into topical sections concerning each of the specific materials and programs in progress. A summary of the tests conducted during this report period is presented in Appendix II together with all of the previous tests from the vacuum creep program. Creep curves for each test conducted during the current reporting period are presented in Appnedix III.

T-111 Test Results

The design characterization of T-111 alloy has been essentially completed with only a small number of conventional T-111 tests still in progress. A Larson-Miller plot of the 1% creep life data developed from this test series is shown in Figure 1.

Preliminary results from the T-111 lithium corrosion loop exposure program are presented in Table 4, and are plotted together with the conventional T-111 test results in Figure 1. The creep test program for this material was originally conceived on the basis of 1000-2000 hour tests. With approximately 60 tests anticipated in the lithium corrosion series, an average test length on the order of 1500 hours would yield a total of about 96,000 test hours (12 specimens test years). However, the data in Figure 1 indicate that the exposed T-111 test material is significantly stronger than any of the heats tested previously, with all of the 1% creep life results obtained to date falling above the previously established T-111 scatter-band. This result means that the tests which were originally calculated to last between 1000 and 2000 hours are actually running for significantly longer times, thereby complicating the experimental program schedule. Thus, in order to limit the total program to a reasonable length, it may be necessary to make the vacuum/lithium exposure comparisons for these lithium exposed specimens on the basis of a Larson-Miller or equivalent parametric type of plot rather than on a direct test-for-test basis.

Concerning the influence of lithium exposure on the creep behavior of the T-111 alloy, only one pair of test results is available to date (S-127 versus S-132). These results show a 1% creep life of 445 hours for the specimen exposed 1000 hours to liquid lithium at 2400°F (1589°K), as compared to 520 hours for the vacuum exposed specimen, indicating no significant influence of the lithium exposure on creep life. It should be emphasized that this result is only preliminary and that additional data which will be developed during the coming report period will be required to determine if the lithium exposure has a significant effect on the creep life of T-111 alloy.

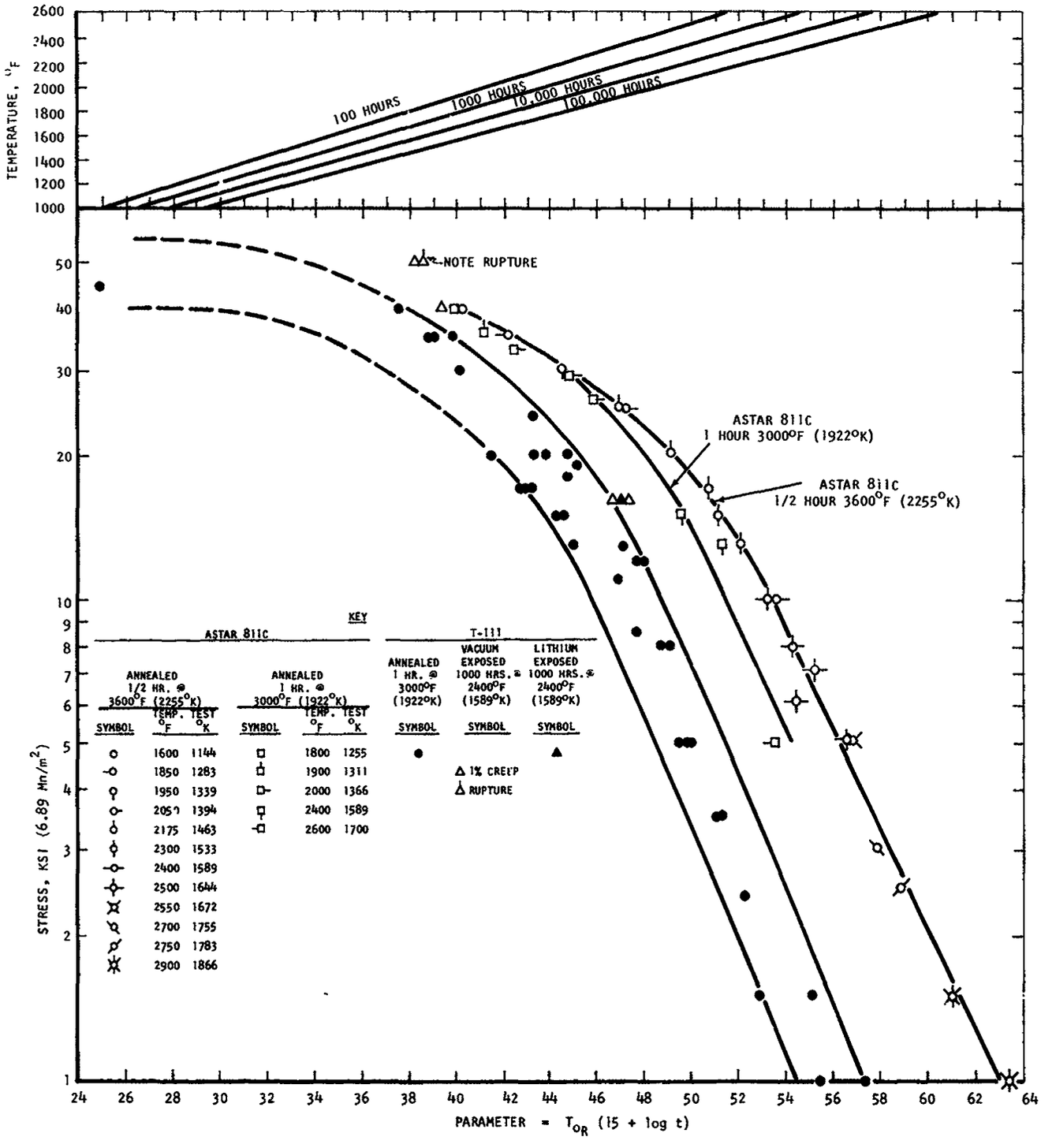

FIGURE 1. LARSON-MILLER PLOT OF 1% CREEP LIFE FOR TANTALUM BASE ALLOYS T-111 AND ASTAR 811C.

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Table 4

Summary of Creep Test Data on Alkali Metal Exposure Specimens

Test No.	Exposure	Stress ksi	Stress mN/m^2	Temperature °F	Temperature K	1% Creep Rate
S-121	1000 hours 2400°F vacuum	40	276	1650	1172	4500*
S-122	" "	50	344	1650	1172	1278**
S-124	" "	16	111	2000	1366	10,000*
S-132	" "	16	111	2200	1478	520*
S-127	1000 hours 2400°F lithium	16	111	2200	1478	445

* Extrapolated
** Ruptured at 1863.3 hours, rupture ductility - 27%

ASTAR 811C Creep Life Results

The ASTAR 811C 1% creep life data generated to date on the program are also plotted on the Larson-Miller diagram in Figure 1. It should be noted that only data from the commercial heat of the ASTAR alloy are shown in this figure, with the earlier data from the laboratory heats having been omitted for the sake of clarity.

The effort to characterize the creep behavior of ASTAR 811C annealed 1/2 hour at 3600°F (2255K) is essentially complete, with only a few tests of material with the high temperature heat treatment still in progress. Preliminary results on ASTAR 811C annealed 1 hour at 3000°F indicate that this annealing treatment produces a lower creep strength at temperatures above 2000°F (1366K). The creep life data at 1800, 1900, and 2000 F (1255, 1311, and 1366K) test temperatures are essentially indistinguishable from the 1/2 hour at 3600°F (2255K) annealing treatment, with the significant differences occurring only at the 2400 and 2600°F (1589 and 1700K) test temperatures. This result is consistent with the previously discussed hypothesis (3) that the increase in creep strength caused by the higher temperature anneal is primarily a grain size effect. The carbide acts predominantly as a grain boundary strengthener in each instance. Since the creep strength of the ASTAR alloy was shown by Buckman (4) to be grain size dependent at and above 2400°F (1589K) but not at 2000°F (1366K), it seems reasonable that the strengthening achieved by increasing the grain size with a high temperature anneal would be effective only in the temperature range where grain boundary sliding occurs. In fact it may well be that the improved strength at lower temperatures is predominately an alloying effect due to rhenium, which is well known to be a potent solid solution strengthening element in tantalum. During the coming report period additional 1% creep life data will be generated on the ASTAR 811C alloy annealed 1 hour at 3000°F (1922K), both for the purpose of developing a well documented design curve for this heat treatment and for the purpose of obtaining additional data for comparison with the 3600°F (2255K) annealing treatment.

ASTAR 811C Creep Rate Analysis

In an effort to gain additional insight into the creep mechanisms in the ASTAR 811C alloy, an analysis was made of the creep rate data from specimens annealed 1/2 hour at 3600°F (2255K). In general, the ASTAR 811C creep curves tended to exhibit the gradually increasing creep rate which is characteristic of the refractory alloys, with slight primary creep appearing only in the temperature ranges below 2000°F (1366K). The minimum creep rates measured from the ASTAR 811C creep curves are shown in Table 5. Note that the value reported at 1600°F (1144K) is tentative, as it is not certain whether this test has yet reached its minimum rate. Two approaches have been used to analyze these rate data. The first approach was the graphical type where the raw data were plotted to determine the stress and temperature dependence of the creep rate. The second approach utilized a computer assisted linear regression analysis to fit the data to various types of creep rate equations. The results of both approaches are described below.

Table 5

Creep Rate Data for ASTAR 811C Annealed
1/2 Hour at 3600°F (2255K)

Test No.	Temperature °F	Temperature K	Stress ksi	Stress mN/m^2	Minimum Creep Rate hr^{-1}
S-94	1600	1144	40	276	8.0×10^{-7}*
S-90	1850	1283	35	241	3.3×10^{-6}
S-91	1950	1339	30	207	2.7×10^{-6}
S-92	2050	1394	25	162	1.5×10^{-6}
S-85	2175	1463	20	138	2.2×10^{-6}
S-76	2175	1463	25	162	1.3×10^{-5}
S-120	2300	1533	13	89.5	8.8×10^{-7}
S-86	2300	1533	15	103	2.0×10^{-6}
S-123	2300	1533	17	117	4.2×10^{-6}
S-77	2400	1589	10	69.0	1.6×10^{-6}
S-74	2400	1589	15	103	1.2×10^{-5}
S-113	2500	1644	5	35.0	6.2×10^{-7}
S-106	2500	1644	6	41.1	1.0×10^{-6}
S-112	2500	1644	7		1.7×10^{-6}
S-95	2500	1644	8	55.1	3.2×10^{-6}
S-119	2500	1644	10	69.0	7.5×10^{-6}
S-78	2550	1672	5	35.0	8.3×10^{-7}
S-93	2700	1755	3	20.7	1.5×10^{-6}
S-96	2750	1783	2.5	16.2	1.5×10^{-6}
S-114	2900	1866	1	6.9	1.2×10^{-6}
S-97	2900	1866	1.5	10.3	5.8×10^{-6}

* Tentative Value - Specimen may not have reached minimum rate when value determined.

The creep rates reported in Table 5 are plotted versus test stress on the customary log-log coordinates in Figure 2. The stress exponent appears to range from about 4 at the higher test temperatures to about 8 at the lower test temperatures, although sufficient data are not available to clearly define a stress exponent below 2175°F (1463K). It was anticipated that this variation of stress exponent with test temperature would make the data difficult to analyze, and the results were therefore replotted on semi-log coordinates to determine if an exponential stress law would yield a more consistent representation. This type of plot, shown in Figure 3, is more consistent with the measurable slopes ranging from .36 to .45, except for the data at 2900°F (1866K). Metallographic examination of a 2900°F (1866K) specimen after testing revealed that grain growth had occurred during the creep test (Figure 4) which may explain the reason for this inconsistency.

In order to further correlate the ASTAR creep rate data, an activation energy for creep was estimated. This was done using the formula:

$$-\Delta H/R = \frac{\ln\dot{\varepsilon}-\ln\dot{\varepsilon}_2}{1/T_2-1/T_1}$$

where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are isostatic creep rates measured at the temperatures T_1 and T_2, respectively (T in °K), R is the universal gas constant (1.987 calories/mole/°K) and ΔH is the apparent activation energy for creep. Application of this formula to the 10 ksi (69 mN/m^2) data at 2400 and 2500°F (1589 and 1644K) yielded an apparent activation energy for creep of approximately 146 Kcal/mole (5000 J/mole) While application to the 15 ksi (103 mN/m^2) data at 2300 and 2400°F (1533 and 1589K) yielded an estimate of 156 Kcal/mole (5340 J/mole). Both of these values seem high when compared with the tantalum self diffusion coefficient of approximately 100 Kcal/mole (3420 J/mole) An explanation for this difference is not currently available.

Using an activation energy of 150 Kcal/mole (5130 J/mole) values of a temperature compensated creep rate parameter of the form:

$$\dot{\varepsilon}e^{\Delta H/RT}$$

were calculated for each test, and these values were plotted on both semi-log and log-log coordinates, Figures 5 and 6. Also shown on these plots, for comparison, are values of the creep rate parameter calculated using the self diffusion activation energy of 100 Kcal/mole (3420 J/mole). These plots do not behave in a typical fashion. For example, the high temperature test data do not correlate well with the rest of the test results. This is understandable in view of the previously noted grain growth observed during testing at the highest test temperature. Of more basic importance, however, is the observation that the slope of the exponential plot, Figure 5, appears to increase at the higher test stresses. The more normal behavior would be for the slope to be constant at the higher stress levels and to decrease at lower

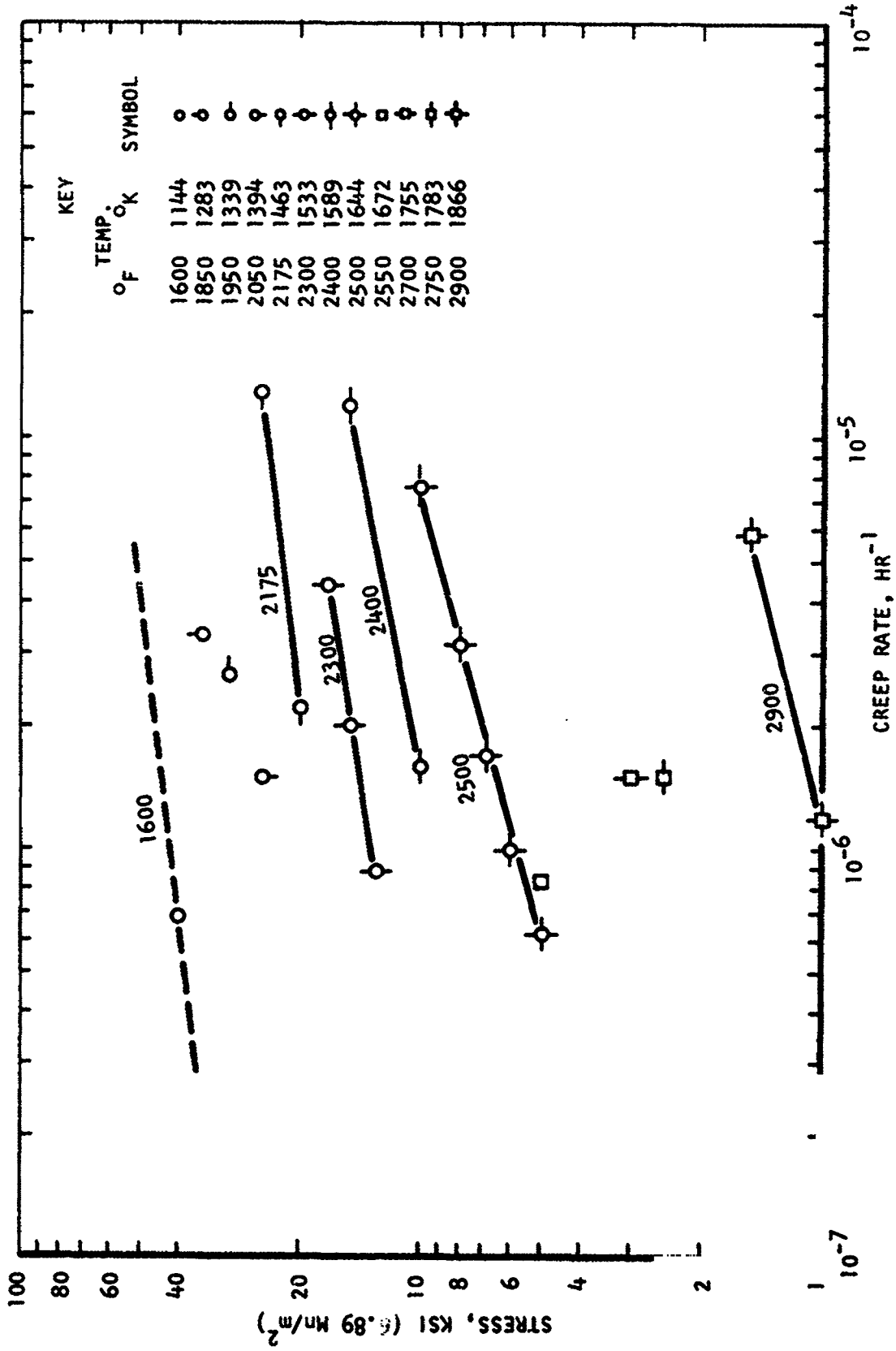


FIGURE 2. LOG-LOG PLOT OF STRESS VERSUS CREEP RATE IN ASTAR 811C ALLOY ANNEALED 1/2 HOUR AT 3600°F (2255°K).

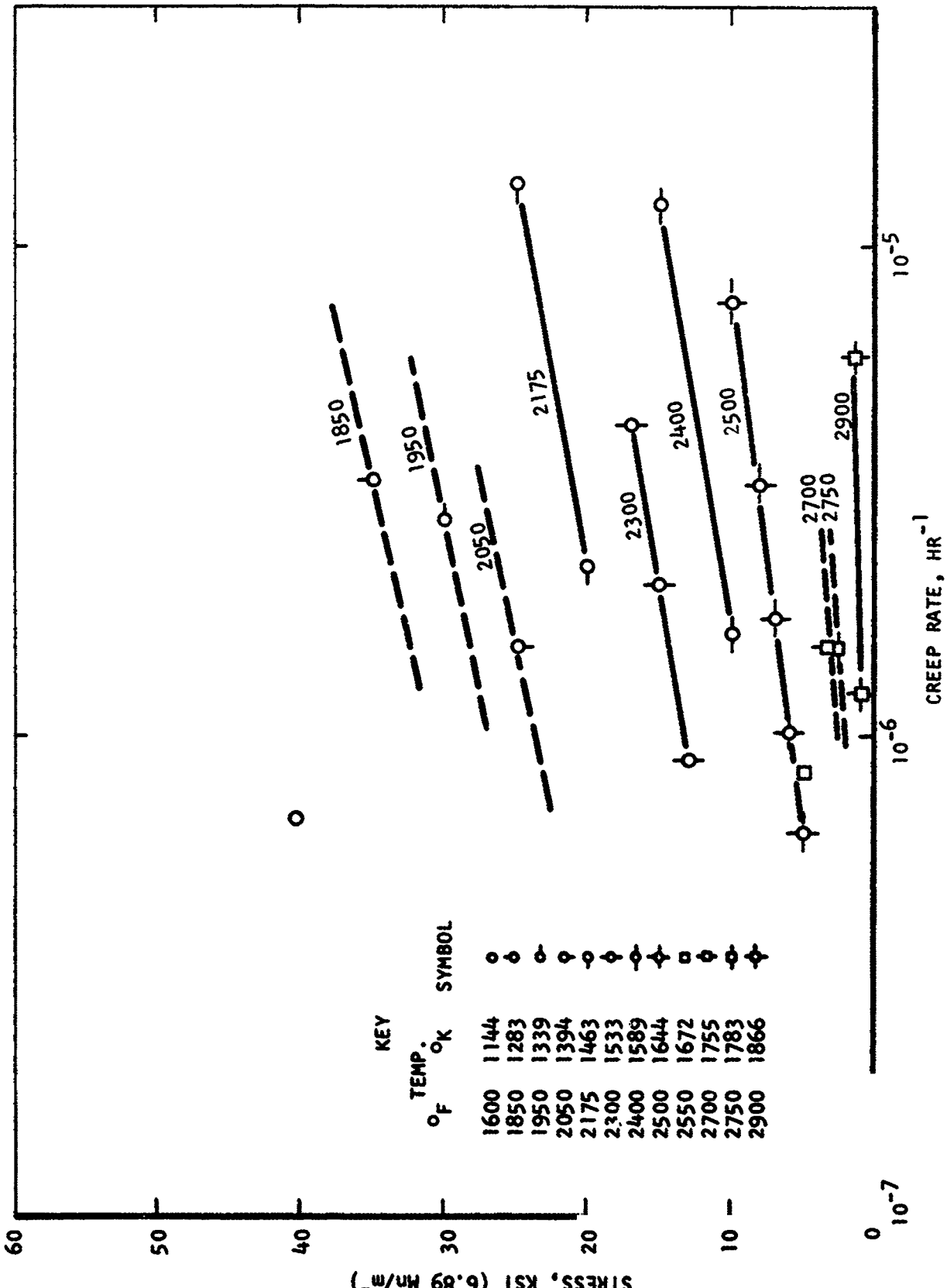
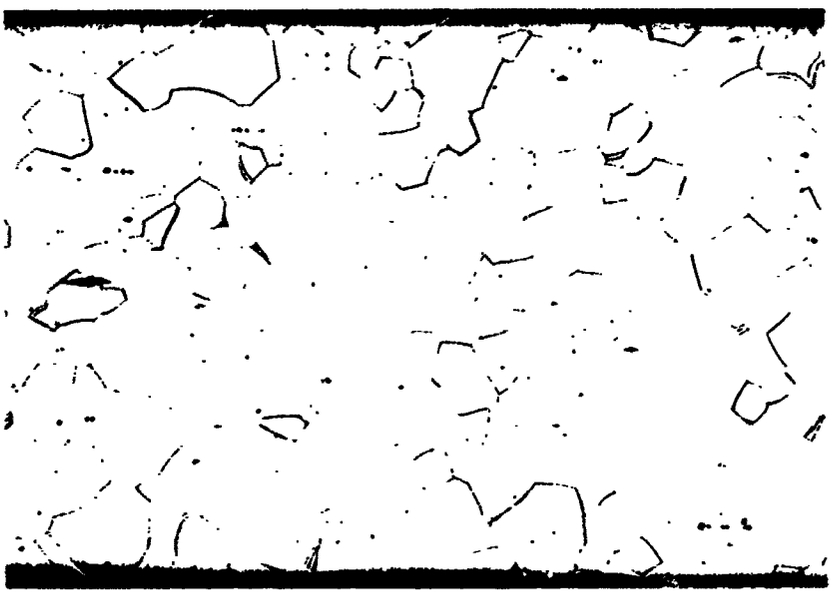
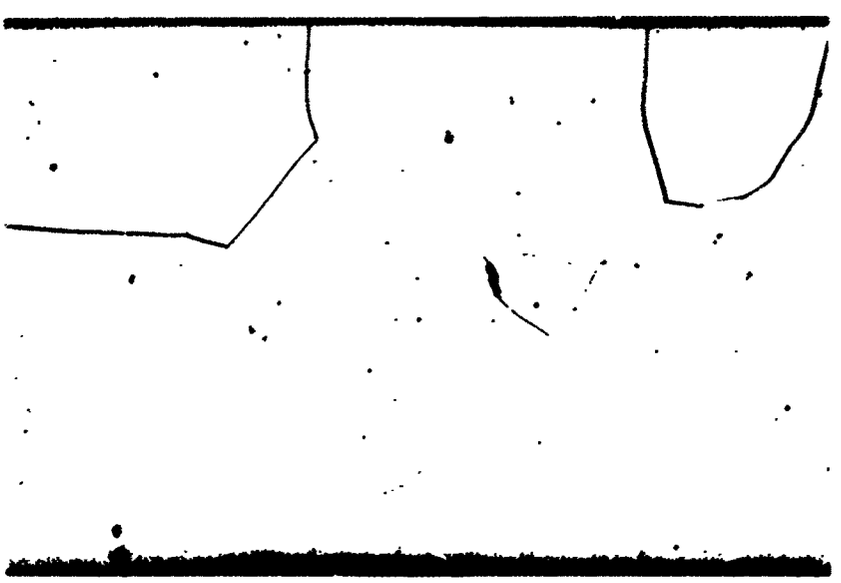


FIGURE 3. SEMI-LOG PLOT OF STRESS VERSUS CREEP RATE FOR ASTAR 811C ALLOY ANNEALED 1/2 HOUR AT 3600°F (2255°K).



ASTAR 811C HEAT 650056 ANNEALED 30 MINUTES AT 3600°F (2255K)



AS ABOVE, CREEP TESTED 4504.7 HOURS AT 2900°F (1866K) AND 1.5 KSI (10.3 mN/m^2) TO A TOTAL CREEP STRAIN OF 4.918%

FIGURE 4. ILLUSTRATING GRAIN GROWTH WHICH OCCURRED DURING CREEP TESTING OF ASTAR 811C ALLOY AT 2900°F (1866K). 100X

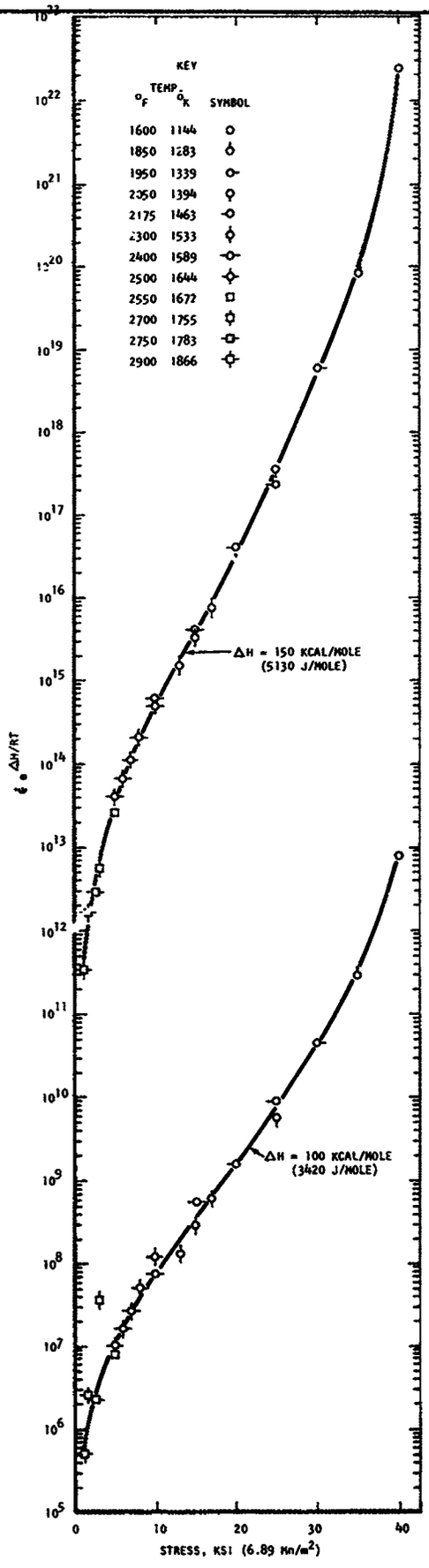


FIGURE 5. SEMI-LOG PLOT OF TEMPERATURE COMPENSATED CREEP RATE VERSUS STRESS FOR ASTAR 811C ANNEALED 1/2 HOUR AT 3600°F (2255°K).

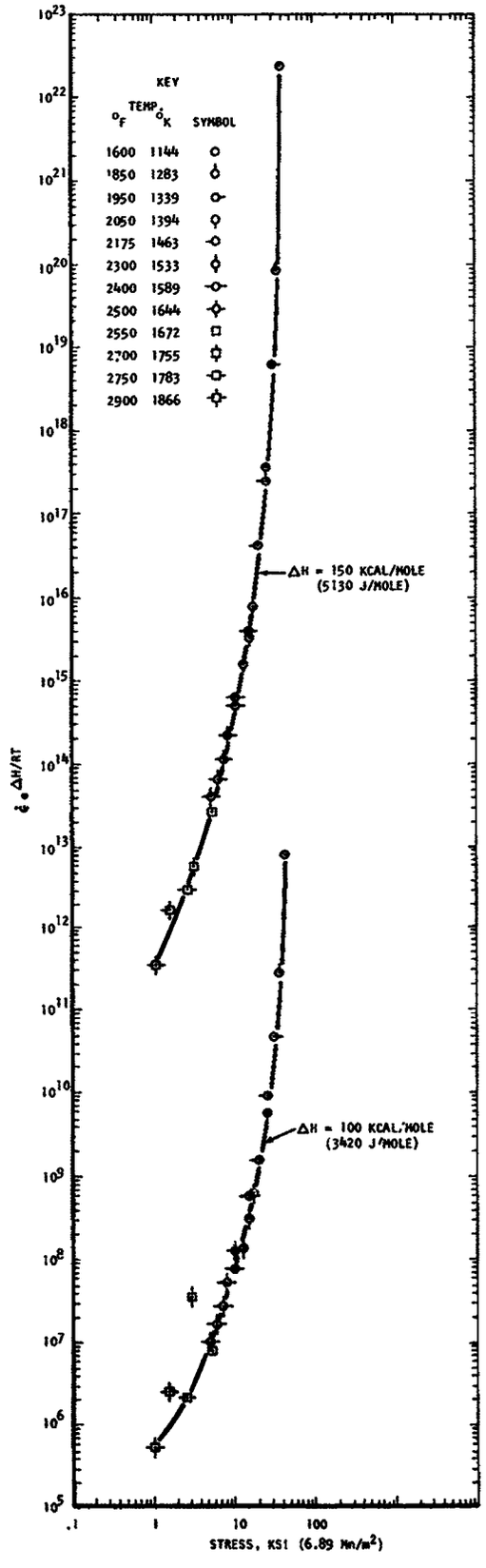


FIGURE 6. LOG-LOG PLOT OF TEMPERATURE COMPENSATED CREEP RATE PARAMETERS VERSUS STRESS FOR ASTAR 811C ANNEALED 1/2 HOUR AT 3600°F (2255°K).

stresses. The observed nontypical behavior of the exponential stress plot leads to the supposition that the activation energy for creep may be changing with temperature, thereby distorting the temperature compensated creep rate plots which are based on constant ΔH values. To test this hypothesis it would be desirable to construct isostatic Arrhenius plots covering the temperature range of interest. This is not possible because of a lack of suitable data in the lower temperature range. The next best approach is to construct a psuedo-Arrhenius type of plot where a stress compensated creep rate parameter of the form

$$\dot{\varepsilon}/f(\sigma)$$

is plotted against reciprocal absolute temperature. One of the common stress laws is generally used for the $F(\sigma)$ function. It has already been demonstrated in Figure 2 that the stress exponent changes significantly with temperature in the ASTAR alloy, making the power law a poor choice for this analysis. The hyperbolic sine law could not be used for the graphical part of the analysis because the unusual high stress behavior of the exponential plot makes it difficult to graphically determine a value of α. (Note the hyperbolic sine law was used successfully in the mathematical part of the analysis discussed below, where a value for α was determined using computerized procedures.) The only choice remaining for the graphical analysis was the exponential law, which was shown in Figure 3 to be relatively consistent at least to 2175°F (1463K). Values of the parameter

$$\dot{\varepsilon}e^{-B\sigma}$$

were therefore calculated for each of the ASTAR creep tests and are plotted versus reciproacl temperature in Figure 7. The plot clearly indicates the change in activation energy with temperature, with the ΔH value varying from approximately 150 Kcal/mole (5130 J/mole) at the top of the plot to approximately 110 Kcal/mole (3760 J/mole) near the bottom of the plot. It is assumed that this change in activation energy is associated with the change in deformation mode from grain boundary sliding to transgranular deformation which was discussed in a previous section.

The other approach used to determine the stress and temperature dependence of creep rate for the ASTAR 811C alloy involved the application of linear regression analysis to determine the values of the constants in the three common creep rate equations:

$$\dot{\varepsilon} = A\sigma^n e^{-\Delta H/RT} \qquad \text{power law} \qquad (1)$$

$$\dot{\varepsilon} = Ae^{B\sigma} e^{-\Delta H/RT} \qquad \text{exponential law} \qquad (2)$$

$$\dot{\varepsilon} = A(\sinh\alpha\sigma)^n e^{-\Delta H/RT} \qquad \text{hyperbolic sine law} \qquad (3)$$

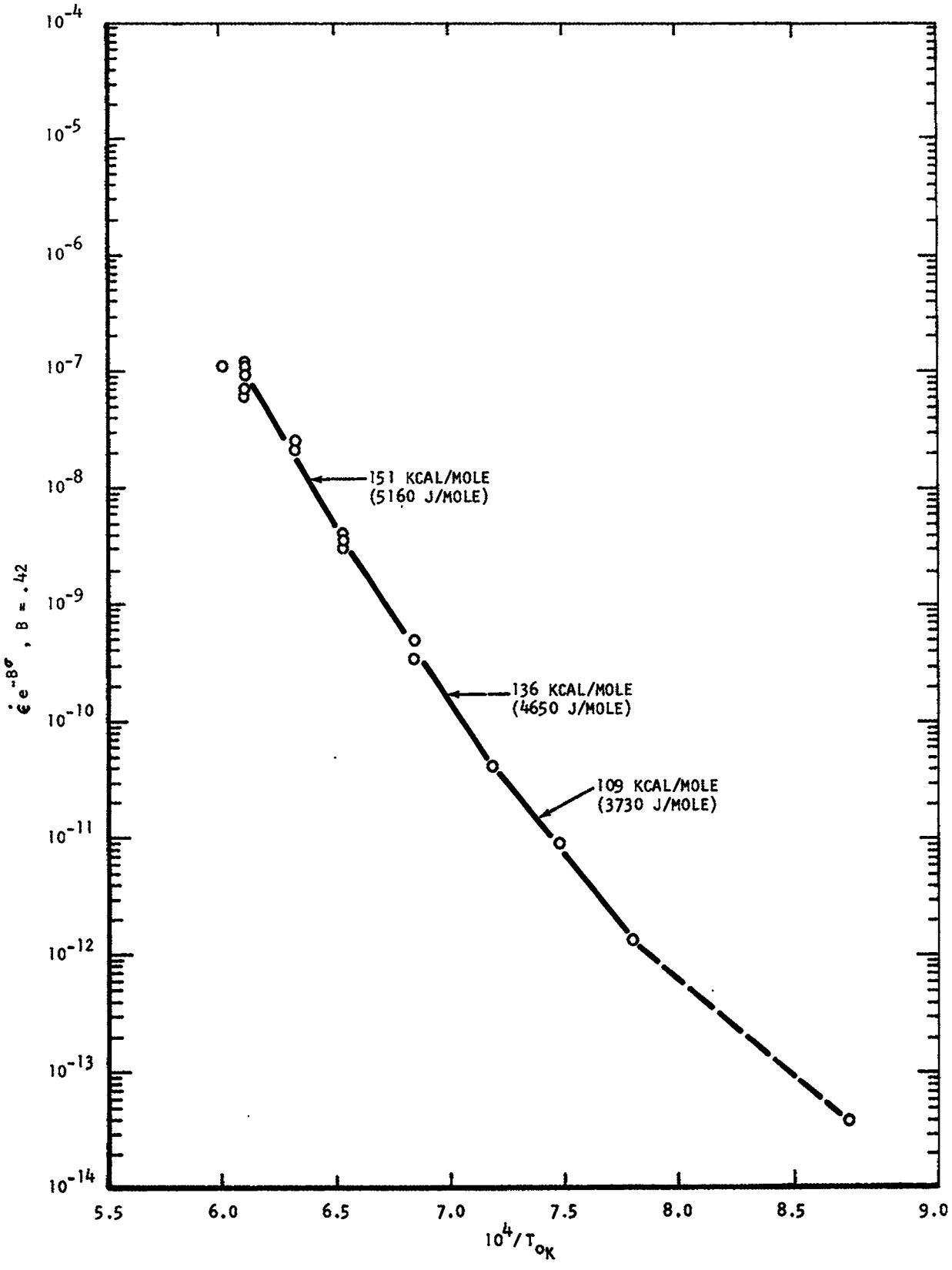


FIGURE 7. ARRHEMIUS PLOT OF STRESS-COMPENSATED CREEP RATE PARAMETER VERSUS RECIPROCAL TEMPERATURE FOR ASTAR 811C ALLOY ANNEALED 1/2 HOUR AT 3600°F (2255°K).

In each case it was necessary to transform the equation by taking the ln of both sides in order to provide a linear form for solution by the linear regression methods:

$$\ln\dot{\varepsilon} = \ln A + n \ln\sigma - \frac{\Delta H}{R}\left(\frac{1}{T}\right) \quad (1A)$$

$$\ln\dot{\varepsilon} = \ln A + B\sigma - \frac{\Delta H}{R}\left(\frac{1}{T}\right) \quad (2A)$$

$$\ln\dot{\varepsilon} = \ln A + n \ln(\sinh\alpha\sigma) - \frac{\Delta H}{R}\left(\frac{1}{T}\right) \quad (3A)$$

The raw creep data were also transformed so that the dependent variable in the regression became $\ln\dot{\varepsilon}$, while the independent variables were (1/T) and $\ln\sigma$, σ, or $\ln(\sinh\alpha\sigma)$, respectively, for the power, experimental, or hyperbolic sine laws. These transformations and the regression analysis were performed on a high speed digital computer using established analytical procedures. Because the constant α enters the Equation 3A nonlinearly, it could not be evaluated directly by the regression method. However, Garofalo (5) has suggested a procedure in which the power and exponential relationships are first evaluated and the constant α is then calculated using the equation $n\alpha = B$. Using this procedure the results shown in Table 6 were calculated for the ASTAR data in Table 5, together with several subsets of the data grouped in different ways according to temperature. In addition to the stress constant and activation energy, the program also calculated the multiple correlation coefficient R^2, which provides a measure of how well the data fit the proposed equation. The closer the value of R^2 is to 1, the better the fit. It is obvious from the results in Table 6 that none of the three equations fit the complete data set adequately, with the highest R^2 value for all of the data being .865. This observation is not surprising in view of the previously noted inconsistency of the very low and very high temperature data points. The analysis was therefore rerun using only the data between 1850 to 2550°F (1283 and 1672K), with a significant improvement in the values of the correlation coefficient. However, even with the obviously inconsistent data eliminated from the analysis, the R^2 values were still relatively low, indicating either that the proposed equations were not suitable for the experimental data, or that the stress parameters and/or activation energy were varying with temperature. It was already known, of course, from the graphical treatments that the activation energy did indeed vary with temperature, so that the obvious next step was to apply the regression analysis to selected subsets of the data grouped to cover relatively narrow temperature ranges. The results of the subset analyses have also been presented in Table 6, and examination of the correlation coefficients shows that high R^2 values can indeed be achieved over the narrower temperature ranges.

Table 6

Results of Least Squares Multiple Linear Regression Analysis of ASTAR 811C Creep Rates From Table 5

Temperature Range, °F	Power Law			Exponential Law			Hyperbolic Sine Law			
	R^2	n	ΔH Kcal per Mole	R^2	n	ΔH Kcal per Mole	α	R^2	n	ΔH Kcal per Mole
All Data	.786	0.94	21.3	.824	.270	72.6	.286	.865	1.00	80.5
1850-2550	.801	2.69	49.5	.958	.406	127	.151	.957	2.35	115
1850-2175	.926	8.89	93.9	.980	.394	112	.044	.959	6.85	104
2175-2300	.992	6.70	109	.999	.369	113	.055	.999	5.11	112
2300-2550	.985	4.19	140	.973	.461	153	.110	.993	3.22	150

Several additional observations concerning the ASTAR 811C creep behavior can be made from analysis of the correlation coefficients in conjunction with the stress parameters and activation energies presented in Table 6. First, it is apparent that both the exponential and the hyperbolic sine equations provide a better fit of the data than the power law in most temperature ranges, with the power law correlation coefficient being in almost all cases the lowest of the three. It is not possible to make a further distinction between the exponential and hyperbolic sine laws, as there seems to be no consistent difference in R^2 values between these two equations. Another observation is that the R^2 values tend to be higher at the higher temperatures where more data are available on the isothermals. This effect is assumed to be a result of the data grouping rather than a real behavior trend. The data in Table 6 also confirm the previously observed variation of activation energy and stress exponent with temperature, as well as the observation that the exponential stress constant shows the greatest consistency of the three stress parameters. The B values range from a low of approximately .37 in the low temperature range to a high of about .46 in the high temperature range. The average of these values is about .415 which is very close to the value of .42 selected for the pseudo-Arrhenius plot shown in Figure 7. The observed ΔH values range from a low of about 110 Kcal/mole (3760 J/mole) in the 1850-2175°F (1283-1463K) range to a high of about 150 Kcal/mole (5130 J/mole) in the 2300-2550°F (1533-1672K) range, again confirming the values obtained graphically from Figure 7. Thus, the results of the regression analysis lead to essentially the same conclusions as the graphical analysis, the most important of which is that the activation energy for creep of the ASTAR 811C alloy annealed 1/2 hour at 3600°F (2255K) changes from a value significantly above the ΔH for self diffusion in a high temperature range where grain boundary sliding is a significant creep mechanism to a value close to the self diffusion value at lower temperatures where intragranular creep appears to be the governing mechanism. Because of this variation of creep mechanism, it is not possible to represent the creep rate of this alloy with a single equation covering the entire temperature range studied.

T-111 Station Function Analysis

The last report on this program (3) described efforts to apply Manson's recently developed station function analysis (6) to the T-111 1% creep life data generated on the vacuum creep program. That effort was not successful because of difficulties encountered with conditioning of the simultaneous equations involved in the analysis. This report will discuss preliminary results from the successful application of an improved version of the station function equation proposed recently by Manson (7). This improved equation avoids some of the difficulties encountered with the earlier version.

Manson's new equation has the general form

$$F(T) \log t + P(T) = G(\log \sigma) \quad (4)$$

with the suggested form for F(T) being

$$F(T) = 1 + AP(T) \quad (5)$$

so that the new relation proposed by Manson takes the specialized form

$$\log t + AP(T) \log t + P(T) = G(\log \sigma) \quad (6)$$

where A is an arbitrary constant to be optimized in the analysis.

Two approaches were suggested for calculating the best value of A (7). The first approach involves solution of Equation (6) with arbitrarily selected values of A ranging from 0.1 to -0.2, with the best value of A being the one which provides the minimum deviation between predicted and experimentally observed values of creep life t. The other approach is to set A to zero, thereby reducing Equation (6) to the form

$$\log t + P(T) = G(\log \sigma) \quad (7)$$

which is solved for P(T). This value of P(T) is then used as a known function in the part of Equation (6) which is multiplied by the unknown A, while P(T) is left as an unknown where it stands alone linearly. A new value of P(T) is determined, which is then used in the same way to determine yet another value of P(T). This process is repeated until successive values of P(T) differ by some arbitrarily small amount, whereupon the constant A is assumed to be optimized.

The work performed during the report period has been concentrated on application of Equation (7) to selected T-111 alloy data. The previous report concerning the original form of the station function Equation (3) described in detail the methods used to establish and solve the set of simultaneous equations generated by application of the station function method and discussed the problem of poor conditioning of the equations developed from the T-111 data. This poor conditioning has continued to be a problem with the newer form of the station function equation, so that it was necessary to examine the T-111 data using the conventional log stress-log creep life type of plot shown in Figure 8 in order to select smoothed data which would yield a set of well conditioned simultaneous equations. The data shown in Figure 8 are clearly separated into two groups, with the isothermals in the strain age strengthened temperature range (below 2000°F) (1366K) being much flatter in slope than those above 2000°F (1366K). It was thought that this inconsistency in the stress exponent might be the cause of the inability to fit the data with a single parameter covering the entire temperature range. As a preliminary step, the following analysis

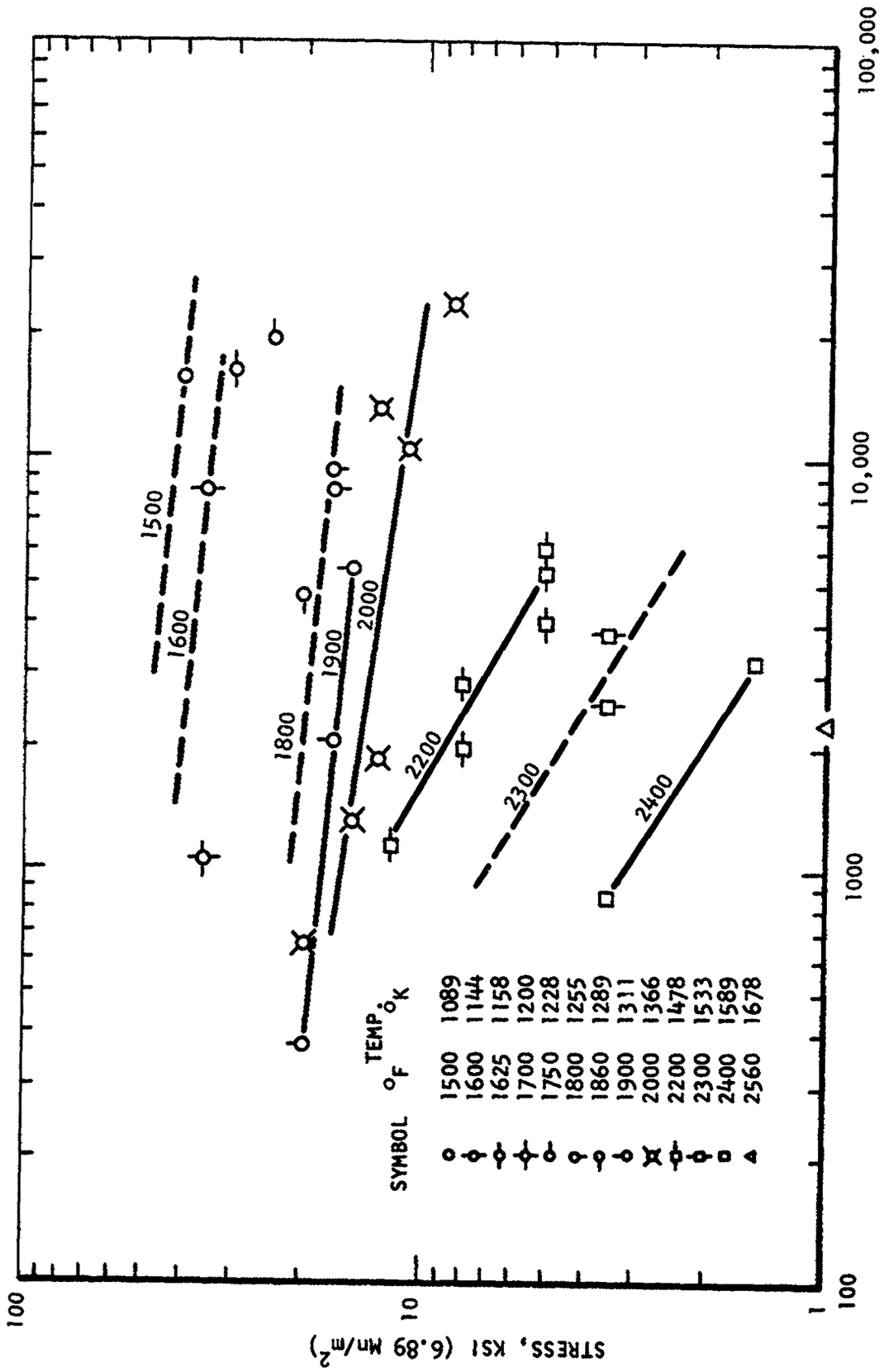


FIGURE 8. 1% CREEP LIFE DATA FOR T-111 ALLOY ANNEALED 1 HOUR AT 3000°F (1922°K).

was therefore performed on smoothed data covering the limited range from 2200 to 2400°F (1478 to 1589K). Elimination of the explicit time function F(log t) from the original form of the station function equation removed the need to select specific time stations for the analysis, thereby reducing the number of unknowns in the equations and the number of data points required for the analysis. For the present case, the thirteen stations listed in Table 7 were selected for application to the thirteen smoothed data points listed in Table 8. Comparison of the stress and temperature stations with the creep data will show that the stations have been tailored to compliment the experimental data, with the station values coinciding with the data wherever possible.

Using the procedures described in the previous report (3), the coefficient matrix shown in Figure 9 was constructed by the application of Equation (7) to each of the experimental data points in Table 8. Each equation represented by this matrix was rearranged to conform to the standard form having all of the unknowns on the left while the known log t term appeared on the right hand side:

$$-G(\log \sigma) + P(T) = -\log t \qquad (8)$$

This coefficient matrix was analyzed using Gauss elimination with complete pivoting, where all pivot elements must satisfy the criterion

$$|a_{ij}| > e$$

where e is a specified arbitrary tolerance level. The analysis was performed on a high speed computer. The subroutine used provided for rearrangement of rows and columns of the successive submatrices so that at each step of the elimination the pivot element represented the largest coefficient in the remaining submatrix. Using this method it was determined that the matrix shown in Figure 9 was singular (i.e., its determinant was zero). The tolerance level generally used for this analysis was 1×10^{-11}, which corresponds approximately to the number of significant figures carried in the calculation.

The Gauss reduction indicated that the rank of the coefficient matrix was 12, that is, it contained a 12 x 12 submatrix which was nonsingular. The result of the rearrangement on reduction showed that the row 6 and column 13 were not contained in the nonsingular submatrix. This result indicates that the thirteenth variable, corresponding to the third temperature function, is dependent, and may be arbitrarily specified. The equation specifying the arbirtrary value for P_3 was inserted in place of Equation 6, which was the row that was shown by the Gauss reduction to be associated with the singularity of the original coefficient matrix. The modified coefficient matrix is thus the same as the original matrix except that row six is replaced with a row whose first twelve elements are zero and whose thirteenth element is one. Application of the Gauss reduction showed that the rank of this matrix was 13, indicating that the modified system was solvable. A Gauss elimination program was therefore applied to solve the matrix equation

Table 7

Stress and Temperature Stations Used In Station Function Analyses

Stress Station	Stress ksi	Stress nM/m^2	Temperature Station	Temperature °F	Temperature K
G_1	1.5	10.3	P_1	2200	1478
G_2	1.9	13.1	P_2	2300	1533
G_3	2.5	17.2	P_3	2400	1589
G_4	3.5	24.1			
G_5	4.5	31.0			
G_6	5.0	34.5			
G_7	6.0	41.3			
G_8	6.5	44.8			
G_9	8.0	55.1			
G_{10}	12.0	82.7			

Table 8

Smoothed T-111 1% Creep Life Data Used In Station Function Analyses

Stress ksi	Stress mN/m^2	Temperature °F	Temperature K	1% Creep Life Hours
1.5	10.3	2400	1589	3250
1.9	13.1	2400	1589	2215
2.5	17.2	2400	1589	1450
3.5	24.1	2400	1589	860
2.5	17.2	2300	1533	5350
3.5	24.1	2300	1533	3188
4.5	31.0	2300	1533	2000
6.0	41.3	2300	1533	1260
4.5	31.0	2200	1478	6400
5.0	34.5	2200	1478	5200
6.5	44.8	2200	1478	3350
8.0	55.1	2200	1478	2475
12.0	82.7	2200	1478	1140

STATION FUNCTION	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	P_1	P_2	P_3
COLUMN	1	2	3	4	5	6	7	8	9	10	11	12	13
ROW													
1	-1	0	0	0	0	0	0	0	0	0	0	0	1
2	0	-1	0	0	0	0	0	0	0	0	0	0	1
3	0	0	-1	0	0	0	0	0	0	0	0	0	1
4	0	0	0	-1	0	0	0	0	0	0	0	0	1
5	0	0	-1	0	0	0	0	0	0	0	0	1	0
6	0	0	0	-1	0	0	0	0	0	0	0	1	0
7	0	0	0	0	-1	0	0	0	0	0	0	1	0
8	0	0	0	0	0	0	-1	0	0	0	0	1	0
9	0	0	0	0	-1	0	0	0	0	0	1	0	0
10	0	0	0	0	0	-1	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	-1	0	0	1	0	0
12	0	0	0	0	0	0	0	0	-1	0	1	0	0
13	0	0	0	0	0	0	0	0	0	-1	1	0	0

FIGURE 9. COEFFICIENT MATRIX FOR STATION FUNCTION ANALYSIS.

$$AX = B$$

where A is the modified coefficient matrix, B is the column vector of log t terms shown in Table 9 (note that the sixth element of this vector is zero, corresponding to the replacement of the sixth row with the equation $P_3 = 0$), and X is a column vector containing the unknowns. The solution vector shown in Table 10 was obtained from the application of the Gauss reduction to the modified system of equations. The first ten elements of this vector correspond to the stress station functions G_1 through G_{10} while the last three elements correspond to the temperature functions P_1 through P_3. Note that the P_3 element is zero, as predetermined by the modification of the sixth equation of the set.

The temperature and stress station functions are plotted against the temperature and stress stations in Figures 10 and 11. Since only three temperature stations were used, it was possible to fit the temperature parameter to an exact second order polynomial:

$$P(T) = C_1 + C_2T + C_3T^2$$

with

$$C_1 = 3.45902$$

$$C_2 = 8.86156 \times 10^{-3}$$

$$C_3 = 3.09179 \times 10^{-6}$$

so that the complete parametric representation of the T-111 creep data in the temperature and stress range of interest becomes

$$\text{Parameter} = P(T) + \log t$$

$$= C_1 + C_2T + C_3T^2 + \log t$$

as indicated in Figure 11. It should be noted that this representation suffers from two significant drawbacks. First, the A constant of Equation (3) has not been optimized. Second, it has been developed with smoothed data over a relatively narrow stress and temperature range. Future work with this method should be directed toward the improvement of the parametric representation in both of these areas.

CVD Tungsten

A program has been undertaken to characterize the creep behavior of chemically vapor deposited tungsten creep specimens. One test has been completed in this series at a temperature of 2912°F (1873K) and a stress of 500 psi (3.5 mN/m^2). This test exhibited a steady state creep rate of 3.3×10^{-7} hr^{-1}

Table 9

Column Vector of Constant log t Terms

-3.511883361
-3.345373731
-3.161368002
-2.934498451
-3.728353782
0
-3.301029996
-3.100370545
-3.806179974
-3.716003344
-3.525044807
-3.393575203
-3.056904851

Table 10

Column Vector of Unknowns

Station Function	Value
G_1	3.511883361
G_2	3.345373731
G_3	3.161368002
G_4	2.934498451
G_5	2.734044216
G_6	2.643867586
G_7	2.533384765
G_8	2.452309049
G_9	2 321439445
G_{10}	1.984769093
P_1	-1.072135758
P_2	-0.566985780
P_3	0

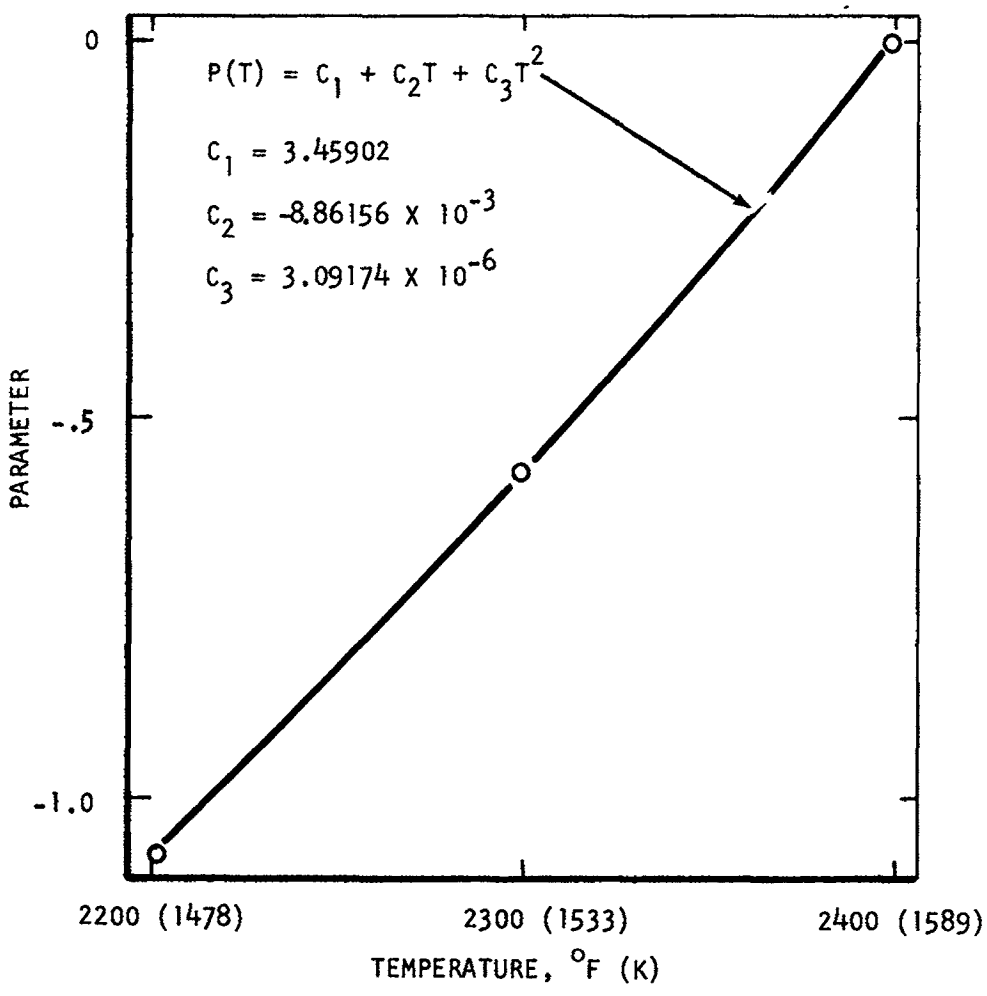


FIGURE 10. PLOT OF TEMPERATURE PARAMETERS CALCULATED FROM STATION FUNCTION ANALYSIS OF T-111 CREEP DATA.

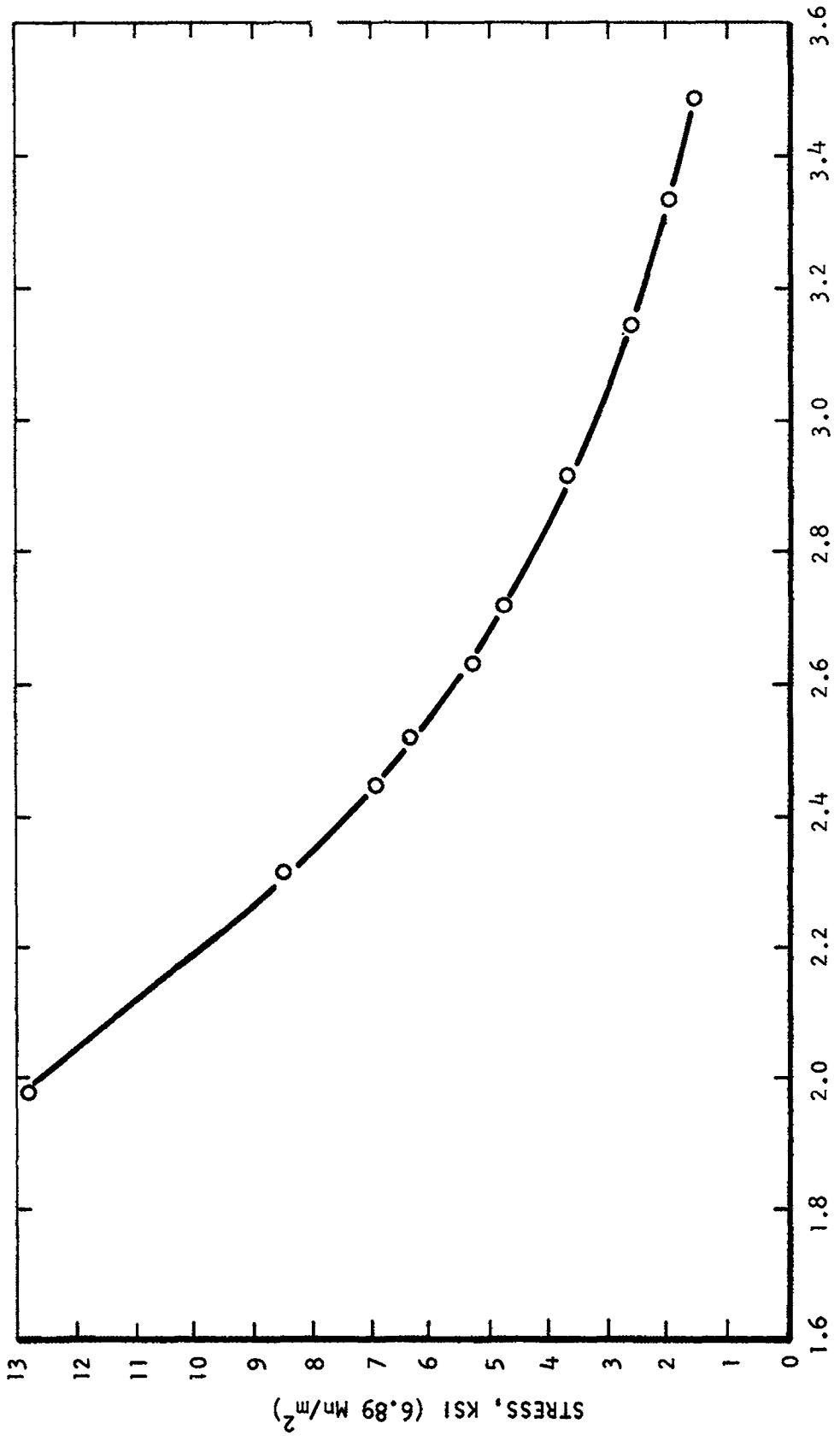


FIGURE 11. PARAMETRIC REPRESENTATION OF T-111 ALLOY CREEP DATA IN THE TEMPERATURE RANGE OF 2200 TO 2400°F (1478 TO 1589°K).

and had an extrapolated 1% creep life of 30,000 hours. A second test, started at 2912°F (1873K) and 1 ksi (6.9 mN/m^2), has an extrapolated 1% creep life of 13,000 hours. Additional tests will be run during the coming report period so that a Larson-Miller plot can be constructed for this material and compared with previous tungsten test results.

Molybdenum Base Alloy TZM

Only one TZM alloy test was in progress during the current reporting period on a specially processed lot of TZM which had a higher than normal carbon content and was forged in the 3400°F (2144K) range to produce an improved carbide dispersion. This test at 2000°F (1366K) and 22 ksi (15.1 x 10^7 mN/m^2) reached 1/2% creep at 16,293 hours, which is significantly longer than anticipated for conventional TZM. While a TZM test would normally be discontinued at 1/2% strain, this test is being continued beyond that point to determine a 1% creep life and to check for possible creep rate instabilities at higher strain levels.

CONCLUSIONS

Ultrahigh vacuum creep test results obtained on T-111 alloy during past report period have been analyzed to show that the 1% creep life of this alloy can be correlated in the range of 2200 to 2400°F (1478 to 1589K) using Manson's recently developed station function analyses. An improved parametric plot of the T-111 1% creep life data is presented to document these results.

Creep testing of paired specimens exposed respectively to liquid lithium and to a 10^{-9} torr vacuum for 1000 hours at 2400°F (1589K) has provided the preliminary indication that the lithium exposure does not have any significant influence on T-111 creep life as compared to vacuum exposure. However, both the vacuum and lithium exposed specimens showed creep lives which were significantly higher than previously obtained T-111 test results. No significant conclusions can be drawn concerning this strength difference until pre-exposure material is obtained for creep testing.

Creep test results on ASTAR 811C alloy have been analyzed for comparison between high temperature and low temperature annealing treatments (1/2 hour at 3600°F (2255K) versus 1 hour at 3000°F (1922K)). Results of this analysis showed that the high temperature annealing treatment is superior to the low temperature treatment only at the lower stresses and higher test temperatures.

Analyses of the minimum creep rate data for ASTAR 811C alloy annealed 1/2 hour at 3600°F (2255K) indicated an activation energy for creep on the order of 150 Kcal/mole (5130 J/mole) in the temperature range near 2400°F (1589K), with the ΔH value dropping to about 110 Kcal/mole (3760 J/mole) at about 2000°F (1366K). This change of activation energy is significant since it corresponds to the temperature range where the creep mechanism appears to change from grain boundary sliding to intragranular creep in this alloy. Comparison of the observed values with the activation energy for self diffusion (on the order of 100-110 Kcal/mole (3420-3760 J/mole)) shows the high temperature creep ΔH to be anomolously high. A good explanation for this finding is not presently available.

Results of the second of a series of creep tests on CVD tungsten annealed 100 hours at 3272°F (2073K) and tested at 2412°F (1873K) and 1 ksi (6.9 mN/m^2) showed this material to have an extrapolated 1% creep life of 13,000 hours at these test conditions.

Results from a specially processed heat of TZM alloy (heat KDTZM-1175) having a higher than normal carbon content and forged at higher than normal temperatures continue to show a creep strength superior to conventional TZM alloy.

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APPENDIX I

PREVIOUSLY PUBLISHED REPORTS

ON THE REFRACTORY ALLOY CREEP PROGRAM

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APPENDIX II

SUMMARY OF ULTRAHIGH VACUUM CREEP TEST RESULTS GENERATED ON THE REFRACTORY ALLOY CREEP PROGRAM

TABLE II-1. Summary of Arc-Melted Tungsten Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-5	KC-1357	24	3200	1760	3.0	20.7	3200	1760	6	32	5.38	57.8
S-7	KC-1357	2	3200	1760	0.4	2.8	3200	1760	***	714	118	***
S-9	KC-1357	2	3200	1760	1.0	6.9	3200	1760	675	3886	2.760	65.4
S-17	KC-1357	2	2800	1538	4.0	28.0	2800	1538	20	908	5.452	53.1
S-18	KC-1357	2	2800	1538	3.0	20.7	2800	1538	125	908	5.535	55.8

***Insufficient creep to extrapolate

TABLE II-2. Summary of Vapor-Deposited Tungsten Ultra-High Vacuum Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{°R}(15+\log t)\times10^{-3}$
B-17	--	1	3200	1760	1.0	6.9	3200	1760	1140	2671	1.570	66.0
B-24	--	1	2800	1538	2.0	13.8	2800	1538	1500	6812	3.708	59.2
S-102	--	100	3272	1800	0.5	3.5	2912	1600	30,000*	2811.5	0.037	65.8
S-117	--	100	3272	1800	1.0	6.9	2912	1600	13,000*	**	**	64.3

*Extrapolated
**In Progress

TABLE II-3. Summary of Tungsten-25% Re Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress KN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{°R}(15+\log t)\times10^{-3}$
S-3	3.5-75002	48	3200	1760	5.0	34.4	3200	1760	12	45	6.03	58.9
S-4	3.5-75002	45	3200	1760	3.0	20.7	3200	1760	25	97	5.22	60.0
S-6	3.5-75002	1	3200	1760	0.5	3.4	3200	1760	***	253	0.090	***
S-8	3.5-75002	1	3200	1760	1.5	10.3	3200	1760	315	1306	5.113	64.0
S-55A	3.5-75002	1	2550	1400	10	68.9	1600	869	--	200	0.005	--
S-55B	3.5-75002		--		10	68.9	1650	900	--	203	0.005	--
S-55C	3.5-75002		--		10	68.9	1700	927	--	196	0.008	--
S-55D	3.5-75002		--		10	68.9	1750	954	--	241	0.018	--
S-55E	3.5-75002		--		10	68.9	1800	980	--	257	0.035	--
S-61A	3.5-75002		--		15	100.4	1600	869	--	235	0.008	--
S-61B	3.5-75002		--		15	100.4	1650	900	--	169	0.022	--
S-61C	3.5-75002		--		15	100.4	1700	927	--	196	0.038	--
S-61D	3.5-75002		--		15	100.4	1750	954	--	200	0.058	--
S-61E	3.5-75002		--		15	100.4	1800	980	--	194	0.078	--

***Insufficient creep to extrapolate

TABLE II-4. Summary of Sylvania A Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{°R}(15+\log t) \times 10^{-3}$
S-12	--	2	3200	1760	5.0	34.4	3200	1760	35	170	5.25	60.6
S-15	--	2	3200	1760	3.0	20.7	3200	1760	250	907	5.862	63.7

TABLE II-5. Summary of AS-30 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T_{°R}(15+\log t)\times10^{-3}$
B-2	C5	As-Rolled			12.0	82.7	2000	1093	390	806	1.020	43.3
B-6	C5	As-Rolled			11.0	75.8	2000	1093	450	1192	1.016	43.5
B-7	C5	As-Rolled			8.0	55.1	2200	1204	115	230	1.025	45.4

Table II-6. Summary of Cb-132M Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T_{°R}(15+\log t)\times10^{-3}$
B-13	KC-1454	1	3092	1700	20.0	138.0	2056	1125	275	568	1.170	43.8
B-14	KC-1454	1	3092	1700	16.3	82.3	2056	1125	340	691	1.026	44.0
B-15	KC-1454	1	3092	1700	7.4	51.0	2256	1236	250	596	1.100	47.2

TABLE II-7. Summary of TZM Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T_{°R}$ (15+logt) x10⁻³
B-1	7502	1	2200	1204	12.6	86.5	2130	1165	605	646	1.105	46.1
B-3	7502	1	2200	1204	10.0	68.9	2000	1095	14,200*	10,048	0.375	47.1
B-29	7502	1	2200	1204	41.0	282.0	2000	1095	100	664	6.215	41.8
B-35	7502	1	2200	1204	44.0	303.0	1800	982	1,000	7659	0.535	42.6
B-4	7502 Plus	1	2200	1204	10.0	68.9	2000	1095	25,000*	10,012	0.368	47.7
		1	2850	1566								
B-16	KDTZM-1175	1	2300	1260	23.4	161.0	1855	1013	62,500*	4376	0.035	45.8
B-18	KDTZM-1175	1	2300	1260	55.0	379.0	1600	871	60,000*	2159	0.018	40.7
B-21	KDTZM-1175	1	2300	1260	65.0	448.0	1600	871	15,000*	1630	0.085	39.5
B-25	KDTZM-1175	1	2300	1260	44.0	303.0	1800	982	50,000*	10,152	0.182	44.5
B-38	KDTZM-1175	1	2300	1260	22.0	151.0	2000	1093	16,293	**	**	47.1
B-34	7463	1/2	2250	1232	41.0	282.0	2000	1093	790	1440	1.658	44.0

*Extrapolated data

**Test in progress

TABLE II-8. Summary of Cb Modified TZM Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T_{°R}(15+\log t) \times 10^{-3}$
B-23A	4305-4	1	2500	1371	20.0	138.0	2000	1093	20,000*	686	0.032	47.5
B-23B	4305-4	-	--	--	28.0	193.0	2000	1093	10,000*	307	0.028	46.7
B-23C	4305-4	-	--	--	40.0	276.0	2000	1093	630*	18	0.188	43.8
B-23D	4305-4	-	--	--	46.0	317.0	1800	982	4000*	403	0.078	42.0
B-23E	4305-4	-	--	--	34.0	234.0	2100	1149	1000*	329	0.170	46.1
B-27	4305-4	1	2500	1371	41.0	282.0	2000	1093	1090	1584	1.040	44.5

*Extrapolated

TABLE II-9. Summary of TZC Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1/2% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1/2% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
B-8A	M-80	1	3092	1700	18.0	124.0	2200	1204	1100	2128	1.060	48.3
B-10	M-80	1	3092	1700	17.0	117.0	2200	1204	2500	2749	0.545	48.9
B-9	M-80	1	3092	1700	20.0	138.0	2000	1093	10,408	16,002	0.670	46.8
B-11	M-80	1	3092	1700	25.0	172.0	1856	1013	75,000*	14,406	0.182	46.0
B-12	M-80	1	3092	1700	19.0	131.0	2056	1125	75,000*	14,239	0.280	49.2
B-20	M-91	1	3092	1700	20.0	138.0	2000	1093	3650	12,795	1.008	45.7
B-31	M-91	1	3092	1700	14.0	96.5	2200	1204	329	912	1.092	46.6
B-19	M-91	1	2300	1260	44.0	303.0	1800	982	1075	4604	1.015	41.1
B-28	M-91	1	2300	1260	28.0	193.0	2000	1093	1100	4214	1.138	44.4
B-30	M-91	1	2500	1371	22.0	152.0	2200	1204	70	259	1.280	44.8
B-32	M-91	1	2500	1371	20.0	138.0	1935	1057	14,400	16,130	0.535	45.9
B-33	M-91	1	2500	1371	22.0	152.0	1900	1038	7720	9697	0.585	44.6
B-36	4345	1	2500	1371	22.0	152.0	2000	1093	5940	8563	0.640	46.2
B-37	4345	1	2400	1316	22.0	152.0	2000	1093	8853	9020	0.500	46.3

*Extrapolated

TABLE II-10. Summary of T-222 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t)\times10^{-3}$
S-13	AL-TA-43	1	3000	1649	12.0	82.7	2200	1204	560	1890	5.720	47.2
S-14	AL-TA-43	1	3000	1649	19.2	132.0	2056	1124	890	1314	1.685	45.1
S-20	AL-TA-43	1	2800	1538	12.0	82.7	2200	1204	405	1389	5.060	46.9

TABLE II-11. Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-29	MASV-20-WS	.5	3600	1982	2.0	13.8	2600	1427	21,190	21,560	1.028	59.3
S-70	VAM-95	.25	3520	1940	20	138.0	2100	1148	3600*	983.4	0.342	47.5
S-71	VAM-95	.15	3600	1982	20	138.0	2100	1148	3600*	767.5	0.320	47.5
S-70A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	655.8	0.108	50.0
S-71A	VAM-95	-	--	--	15	103.0	2200	1204	6000*	678.9	0.112	50.0
S-70B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1106.4	0.153	51.9
S-71B	VAM-95	-	--	--	10	69.0	2300	1263	6000*	1082.2	0.178	51.9
S-73	VAM-95	.33	3600	1982	15	103.0	2400	1316	435	720.5	1.860	50.5
S-74	650056	.33	3600	1982	15	103.0	2400	1316	825	1466.0	2.185	51.2
S-75	VAM-95	1.0	3000	1649	15	103.0	2400	1316	144	162.3	1.195	49.1
S-76	650056	.5	3600	1982	25	162.0	2175	1191	695	4962.5	15.088	47.0
S-77	650056	.5	3600	1982	10	69.0	2400	1316	5287	5907.9	1.150	53.6
S-78	650056	.5	3600	1982	5	35.0	2550	1399	5611	6210.4	1.210	56.6
S-79	VAM-95	5	3450	1800	15	103.0	2400	1316	542	714	1.378	50.8
S-81	VAM-95	24	3270	1700	15	103.0	2400	1316	560	666.5	1.330	50.8
S-85	650056	.5	3600	1982	20	138.0	2175	1191	4410	5346.7	1.240	49.1
S-86	650056	.5	3600	1982	15	103.0	2300	1263	4390	5206.1	1.240	51.1

*Extrapolated

TABLE II-11. Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-87+	NASV-20	1	3000	1649	15	103.0	2400	1316	68	329	11.470	48.1
S-100++	NASV-20	1	3000	1649	15	103.0	2400	1316	152	330.9	10.750	49.1
S-104+	NASV-20	1	3000	1649	8	55.1	2400	1316	1575	1777.0	1.206	52.1
S-108++	NASV-20	1	3000	1649	8	55.1	2400	1316	1694	2851.9	1.506	52.3
S-90	650056	0.5	3600	1982	35	241.0	1850	1010	1858	4323.6	2.402	42.2
S-91	650056	0.5	3600	1982	30	207.0	1950	1066	2656	6385.0	2.018	44.5
S-92	650056	0.5	3600	1982	25	162.0	2050	1121	6095	6763.6	1.095	47.2
S-93	650056	0.5	3600	1982	3	20.7	2700	1482	2064	4364.0	3.798	57.9
S-94	650056	0.5	3600	1982	40	276.0	1600	871	35,000*	**	**	40.2
S-95	650056	0.5	3600	1982	8	55.1	2500	1371	2266	3963.8	2.392	54.3
S-96	650056	0.5	3600	1982	2.5	16.2	2750	1510	2270	5303.4	3.552	58.9
S-97	650056	0.5	3600	1982	1.5	10.3	2900	1593	1580	4504.7	4.918	61.1
S-101	650056	1	3000	1649	15	103.0	2400	1316	230	673.9	12.182	49.6
S-106	650056	0.5	3600	1982	6	41.4	2500	1371	2778	2971.2	1.160	54.5
S-112	650056	0.5	3600	1982	7	48.2	2500	1371	4420	**	**	55.2

*Extrapolated
**Test In Progress

+Post Exposure Samples From G.E. Alkali Metal Exposure Program
++Pre-Exposure Samples From G.E. Alkali Metal Exposure Program

C-2

TABLE II-11. Summary of ASTAR 811C Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{o_R}(15+\log t) \times 10^{-3}$
S-113	650056	0.5	3600	1982	5	34.4	2500	1371	15,000*	**	**	56.7
S-114	650056	0.5	3600	1982	1	6.9	2900	1593	8000*	**	**	63.5
S-118	650056	1	3000	1649	29	199.8	2000	1093	1620	1655.3	1.010	44.8
S-119	650056	0.5	3600	1982	10	68.9	2500	1371	1035	1145.3	1.178	53.3
S-120	650056	0.5	3600	1982	13	89.5	2300	1263	9000*	**	**	52.3
S-123	650056	0.5	3600	1982	17	117.0	2300	1263	2100*	**	**	50.6
S-125	650056	1	3000	1649	23	158.3	2000	1093	***	**	**	***
S-126	650056	1	3000	1649	26	179.0	2000	1093	4200	**	**	45.8

*Extrapolated
**Test In Progress
***Insufficient to Extrapolate

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-16	70616	1	2600	1427	8.0	55.1	2200	1204	725	1675	2.570	47.5
S-19	70616	1	3000	1649	8.0	55.1	2200	1204	2000	4870	3.368	48.7
S-21	70616	1	3000	1649	12.0	82.6	2200	1204	1140	3840	6.548	48.0
S-23	70616	1	3000	1649	12.0	82.6	2120	1160	3150	3698	1.225	47.7
S-22	70616	1	3000	1649	20.0	138.0	2000	1093	670	1099	2.010	43.8
S-24	70616	1	3000	1649	20.0	138.0	1860	1016	4730	4946	1.090	43.3
S-25	D-1670	1	3000	1649	15.0	103.0	2000	1093	1340	1584	1.210	44.6
S-26	D-1670	1	3000	1649	17.0	117.0	1800	982	9540	9624	1.030	42.9
S-25A	D-1670	1	3000	1649	1.5	10.3	2600	1427	1100*	482	0.632	55.2
S-28	D-1670	1	3000	1649	0.5	3.4	2600	1427	640,000*	38,129.3	0.568	63.7
S-27	D-1102	1	3000	1649	13.0	89.5	2000	1093	1880	3459	2.082	45.0
S-32	D-1102	1	3000	1649	5.0	34.4	2200	1204	4050	4322	1.042	49.5
S-40	D-1102	1	3000	1049	17.0	117.0	1800	982	8558	8717	1.028	42.8
S-33	65076	1	3000	1649	8.0	55.1	2200	1204	2850	2976	1.048	49.1
S-34	65076	1	3000	1649	11.0	75.8	2000	1093	10,800	10,875	1.010	46.9
S-37	65080	1	3000	1649	8.0	55.1	2200	1204	260	274	1.230	46.3
S-39	65080	1	3000	1649	13.0	89.5	1800	982	8202	8728	1.070	42.7
S-45	65080	1	3000	1649	3.0	20.0	2200	1204	554	697	1.165	47.1
S-30	65079	1	3000	1649	3.5	24.1	2400	1316	860	2137	2.372	51.3

*Extrapolated
**Test in progress

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-31	65079	1	3000	1649	5.0	34.4	2200	1204	6160	6594	1.092	50.0
S-35	65079	1	3000	1649	5.0	34.4	2200	1204	5400	5522	1.048	49.9
S-42	65079	1	3000	1649	3.5	24.1	2300	1263	3810	4247	1.122	51.3
S-47	65079	1	3000	1649	24.0	165.0	1750	954	19,896	22,476.2	1.298	43.3
S-48	65079	1	3000	1649	2.4	165.0	2330	1275	5500	6284	1.200	52.3
S-50	65079	1	3000	1649	8.5	72.2	2000	1093	24,000*	5735	0.272	47.7
S-43	65079	1/4	3000	1649	18.0	124.0	2000	1093	1500*	361	0.108	44.7
S-44A	65079	1	3000	1649	9.5	65.5	2172	1189	3250*	467	0.152	48.7
S-44B	65079	1/4	3000	1649	3.3	22.7	2371	1299	2030*	335	0.168	51.9
S-44C	65079	1/4	3000	1649	18.0	124.0	2000	1093	1670*	1146	0.688	44.8
S-44D	65079	1/4	3000	1649	23.0	158.0	1800	982	14,650*	1391	0.112	43.3
S-59	D-1183	1	3000	1649	13.0	89.5	2000	1093	13,350	15,219.0	1.192	47.1
S-60	D-1183	1	3000	1649	35.0	241.0	1600	870	8550	17,794.5	11.218	39.0
S-68	650028	1	3000	1649	1.0	6.9	2560	1403	2300	14,783.9	1.660	55.5
S-69	650028	1	3000	1649	30.0	207.0	1625	885	16,625	18,120.7	1.312	40.1
B-43	650028	1	3000	1649	20.0	138.0	2000	1093	1823	1840.8	1.012	44.8
B-44	650038	1	3000	1649	35.0	241.0	2000	1093	1093	55.1	7.582	39.8
P-1	8049	1	3000	1649	19.0	131.0	2000	1093	2070	3649	2.142	45.1
S-80	650028	1	3000	1649	37.0	255.0	1300	704	***	3192.8	0.775	***

*Extrapolated

TABLE II-12. Summary of T-111 Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T\theta_R(15+\log t) \times 10^{-3}$
S-82A	650028	-	--	--	50.0	344.0	900	482	***	5610.8	0.075	***
S-83	650028	1	3000	1649	45.0	310.0	1100	593	7	1177.1	2.945	24.8
S-84	650028	1	3000	1649	1.5	10.4	2400	1316	3250	5273.6	1.502	52.9
S-41	65080	15	3000	1649	8.0	55.1	2200	1204	234	259	1.080	46.2
S-98	848001	1	3000	1649	1	6.9	2560	1404	12,000*	**	**	57.4
S-99	650028	1	3000	1649	0.5	3.5	2700	1482	250,000*	**	**	64.5
S-103	650028	1	3000	1649	40	276.0	1500	816	16,000*	**	**	37.6
S-105	650028	1	3000	1649	35	241.0	1700	929	1060	3211.6	8.990	39.0
S-107	848001	1	3000	1649	20	138.0	1900	1038	380	1197.6	3.042	41.5
S-115	848001	1	3000	1649	17	117.0	1900	1038	2100	2106.7	1.002	43.2
S-116	848001	1	3000	1649	15	103.3	1900	1038	6000*	**	**	44.3
S-121	+	As Received			40	276.0	1650	899	4500*	**	**	39.4
S-122	+	As Received			50	344.0	1650	899	1278	1863.3	22++	38.2
S-124	+	As Received			16	111.0	2000	1092	10,000*	**	**	46.7

*Extrapolated
**Test in Progress
***Insufficient to Extrapolate

+G.E.Lithium Corrosion Loop Exposure Specimens
++Estimated Rupture Ductility - Specimen Ruptured

TABLE II-13. Summary of T-111 Linearly Increasing Stress Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress Rate PSI/Hr	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep
S-36	65080	1	3000	1649	16	2200	1204	600	624	1.120
S-38	65080	1	3000	1649	1	2200	1204	3830	4686	1.562
S-46	65079	1	3000	1649	16	2200	1204	1000*	761	0.225
S-49	65079	1	3000	1649	20	1800	982	1660	1964	5.125
S-51	D-1183	1	3000	1649	16	2200	1204	1080	1274	5.823
S-52	65079	1	3000	1649	13	2000	1093	1596	1657	1.150
S-53	65079	1	3000	1649	5	2200	1204	2240	2970	5.292
S-54	65079	1	3000	1649	5	2000	1093	3850	6506	6.478
S-56	65079	1	3000	1649	5	1800	982	5500	6375	5.280
S-57	65079	1	3000	1649	1	2200	1204	7748	8833	1.510
S-62	65079	1	3000	1649	2	2000	1093	8300	8599	1.150

*Extrapolated

TABLE II-14. Summary of Pure Ta Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{°R}(15+\log t) \times 10^{-3}$
B-39A	B-1962	1	1832	1000	13.6	93.7	1100	596	31	32	1.020	25.8
B-39B	B-1962	1/4	1832	1000	11.6	79.9	1100	596	603*	264	0.542	27.8
B-39C	B-1962	1/4	1832	1000	10.1	69.5	1183	639	463*	282	0.635	29.0
B-40A	B-1962	1	1832	1000	7.0	48.3	1350	732	9	9	1.000	28.9
B-40B	B-1962	1/4	1832	1000	4.9	33.8	1350	732	6600*	1386	0.300	34.0
B-41	B-1962	1	1832	1000	11.1	76.5	1100	596	144	160	1.078	26.7
B-42A	B-1962	1	1832	1000	4.0	27.5	1350	732	170	186	1.015	31.2
B-42B	B-1962	1/4	1832	1000	4.0	27.5	1350	732	2070	1775	0.892	33.1
B-45	60249	0.1	2290	1255	4.0	27.5	1350	732	***	69.6	0.002	***
B-45B	60249	0.1	2290	1255	8.0	55.0	1350	732	520	1800	1.823	32.0
B-46	60249	0.1	2290	1255	6.5	44.8	1350	732	5600*	155.8	0.215	34.0
B-47++	60249	0.1	2290	1255	16 psi/hour		1350	732	544	548.3	1.050	--
B-47A	60249	-	--	--	8.0	55.0	1350	732	714	907	1.190	32.3
B-48A+	60249	0.1	2290	1255	6.5	44.8	1450	788	252	2371	2.885	33.2

*Extrapolated
***Insufficient creep to extrapolate
+Welded
++Linearly increasing stress

TABLE II-14. Summary of Pure Ta Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_{°R}(15+\log t) \times 10^{-3}$
B-48B+	60249	-	--	--	7.5	52.3	1450	788	150	1177.2	3.212	32.8
B-49	60249	0.1	2290	1255	6.5	44.8	1450	788	92	2175.4	3.372	32.4
B-49A	60249	-	--	--	7.5	52.3	1450	788	180	1363.9	3.282	33.0
B-49B	60249	-	--	--	9.0	62.1	1450	788	24	497.8	5.698	31.3
B-51	60379	0.1	2290	1255	6.5	44.8	1350	732	26	2712.0	4.412	29.8
B-52	60065	0.1	2290	1255	6.5	44.8	1350	732	17,000*	2062	0.115	34.8
B-53	60381	0.1	2290	1255	6.5	44.8	1350	732	12,000*	6930.9	0.858	34.5
P-2	818072	++	++	++	6.5	44.8	1350	732	1.6	649.7	4.685	27.5
P-3	B-1960	++	++	++	6.5	44.8	1350	732	60	6096.2	3.168	30.4
P-4	B-1960	++	++	++	6.5	44.8	1350	732	30	5689.4	4.230	29.8
P-5	B-1960	++	++	++	6.5	44.8	1350	732	110,000*	4900.5	0.155	36.3

*Extrapolated
**Pre-strained 30% in tension prior to testing
+Welded
++Not available

TABLE II-15. Summary of Ta-10W Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Test Temperature °F	Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	1% Creep Larson-Miller Parameter $T_R(15+\log t) \times 10^{-3}$
S-58A	630002	1	3000	1649	20	38.0	2100	1148	285	308	1.125	44.7
S-58B	630002	1/4	3000	1649	11.5	79.3	2210	1209	770*	410	0.572	47.7
S-58C	630002	1/4	3000	1649	6.2	42.7	2320	1268	2200*	700	0.330	51.0
S-58D	630002	1/4	3000	1649	3.5	24.1	2430	1332	10,200*	1290	0.202	54.9
S-64	630002	1	3000	1649	16	111.0	2000	1093	250	266	1.060	42.8
S-66	630002	1	3000	1649	16	111.0	2000	1093	135	550	5.150	42.1
S-67	630002	1	3000	1649	12	82.9	2000	1093	5227	6098	1.270	46.0

*Extrapolated

TABLE II-16. Summary of T-111 Linearly Decreasing 1 Progressive Temperature Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress KSI	Stress MN/M²	Starting Test Temperature °F	Starting Test Temperature °C	1% Creep Life Hours	Termination of Test Time, Hours	Termination of Test Percent Creep	Rate of Temperature Decrease F°/hr
S-65	65079	1	3000	1649	7	48.2	2400	1316	--	1850	0.105	0.6
S-72	650028	1	3000	1649	7	48.2	2400	1316	370	1322.1	1.282	0.3
S-82	650028	1	3000	1649	31	214.0	1900	1038	235	2013.8	1.180	0.5

TABLE II-17. Summary of T-111 Exponentially Varying Stress and Temperature Ultra-High Vacuum Creep Test Results

Test No.	Heat No.	Heat Treatment Time Hours	Heat Treatment Temperature °F	Heat Treatment Temperature °C	Stress Level (Dimensionless)	Starting Temperature °F	Starting Temperature °C	Half Life (Hours)	Stall Strain Percent	Termination of Test Time, Hours	Termination of Test Percent Creep
S-109	650028	1	3000	1649	1	2600	1427	400	2.830	600.0	2.702
S-110	650028	1	3000	1649	1	2600	1427	100	1.038	192.2	0.795
S-111	650028	1	3000	1649	1	2600	1427	170	1.5*	**	**

*Estimated
**Test in Progress

APPENDIX : II

CREEP CURVES

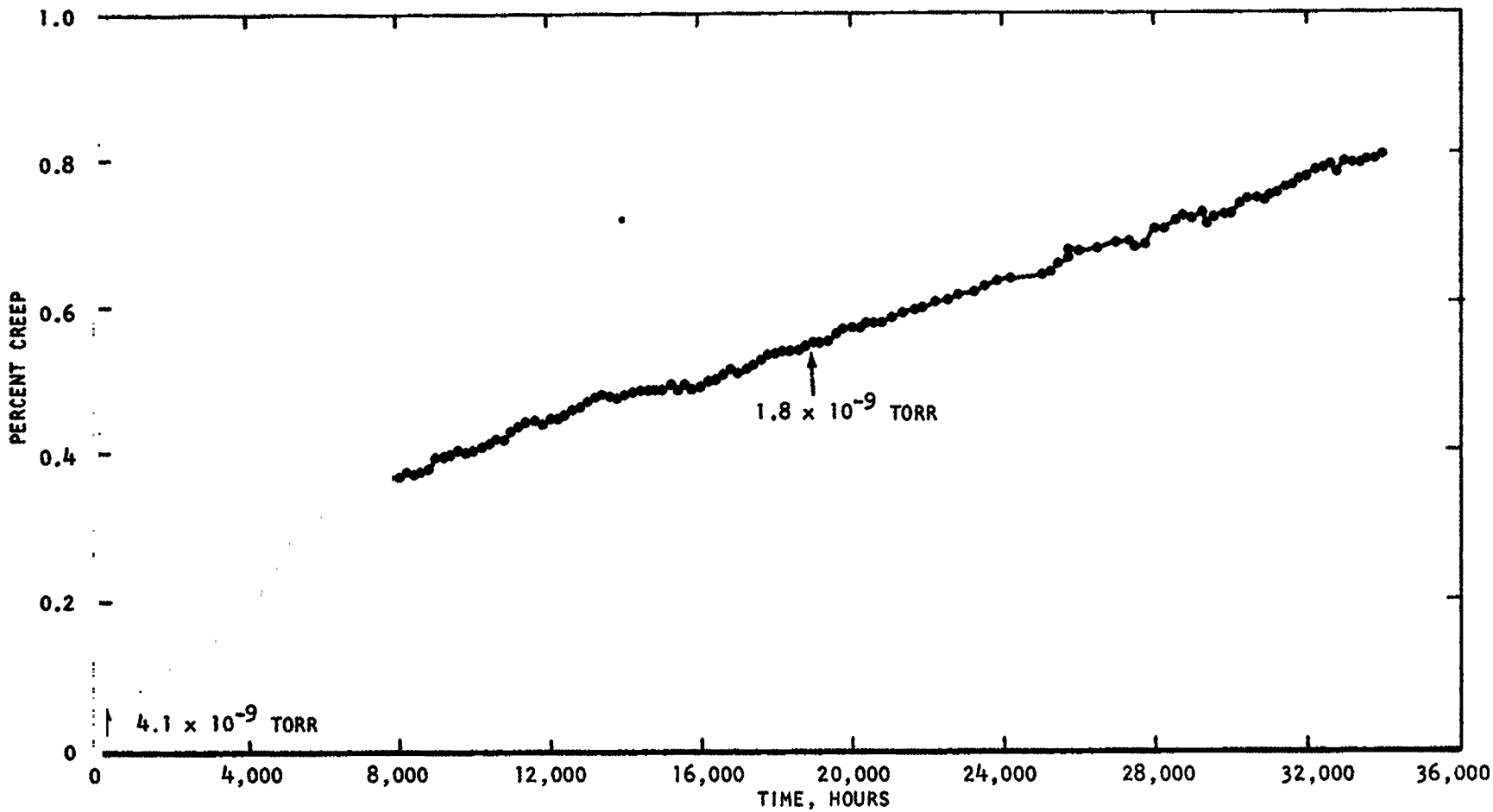

FIGURE III-1. CREEP TEST DATA, TZM HEAT NO. KDTZM-1175 STRESS RELIEVED 1 HOUR AT 2300°F (1260°C), TESTED AT 2000°F (1093°C) AND 22 KSI (151 nM/m^2), TEST NO. B-38, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

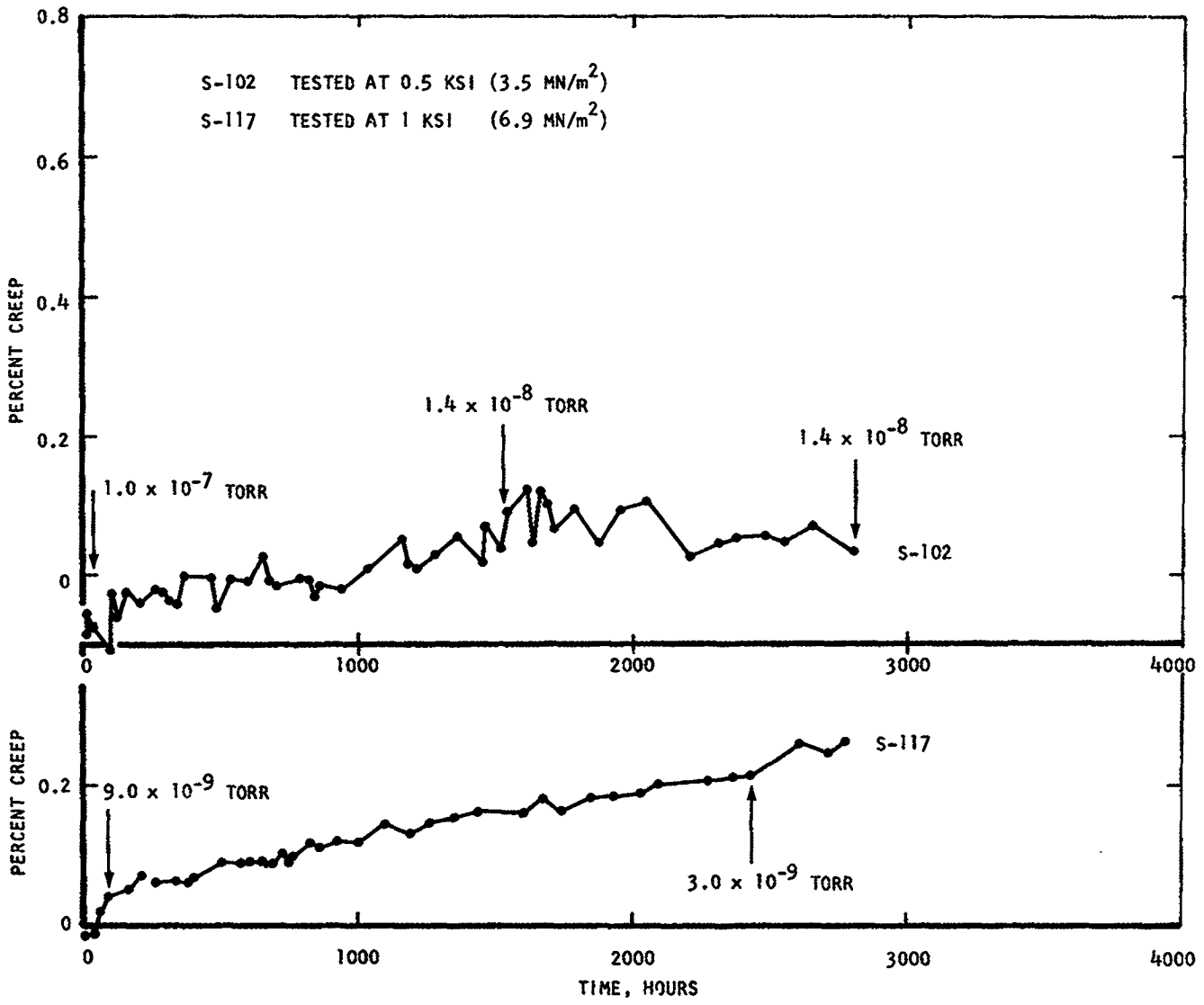

FIGURE III-2. CREEP TEST DATA, CVD-W ANNEALED 100 HOURS AT 3272°F (1800°C), TESTED AT 2912°F (1600°C), TEST NOS. S-102 AND S-117, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

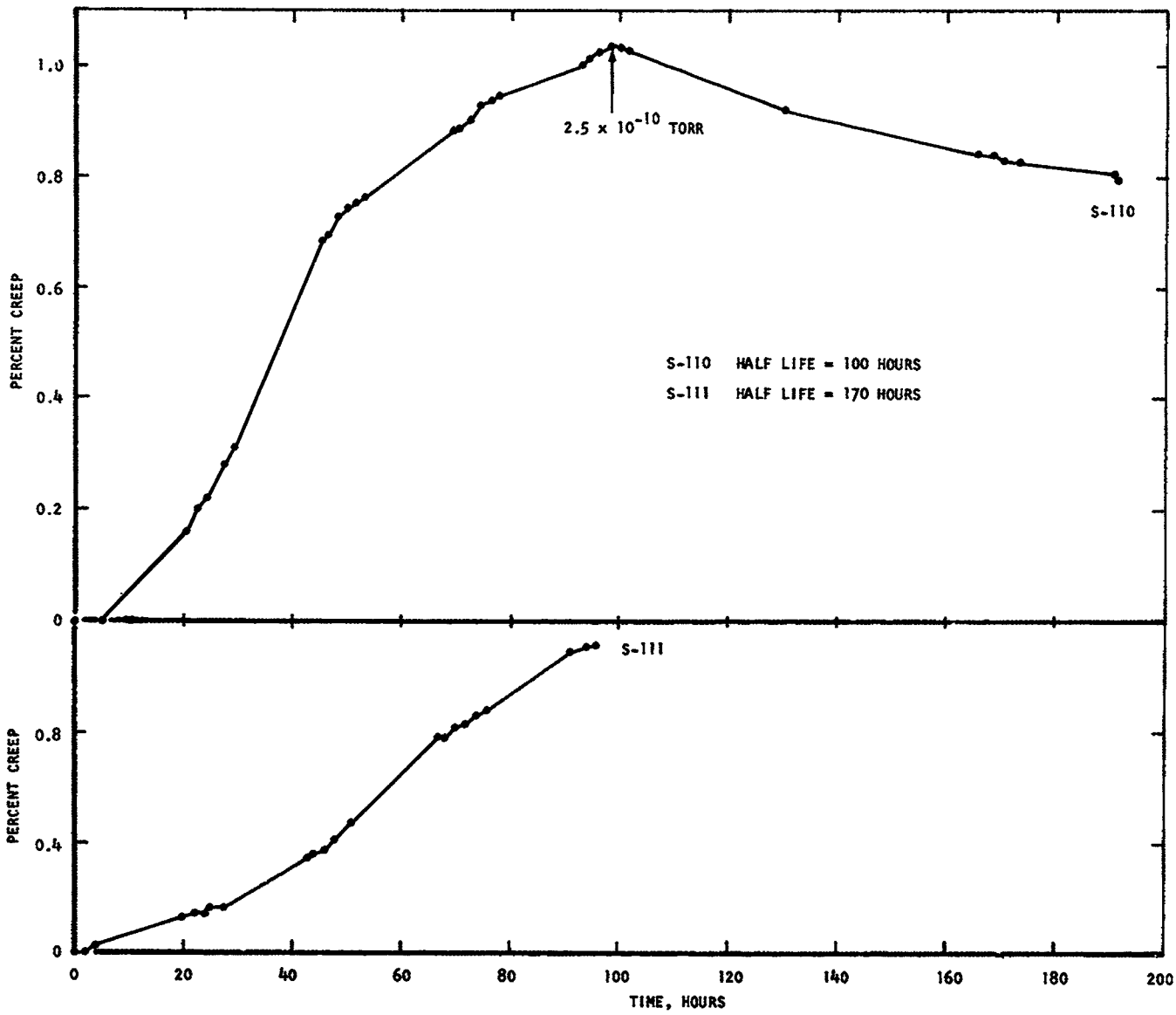

FIGURE III-3. CREEP TEST DATA, T-111 HEAT NO. 650028 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED WITH CONTINUOUSLY VARYING STRESS AND TEMPERATURE. STARTING TEMPERATURE 2600°F (1427°C), STRESS LEVEL = 1, TEST NOS. S-110 AND S-111, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

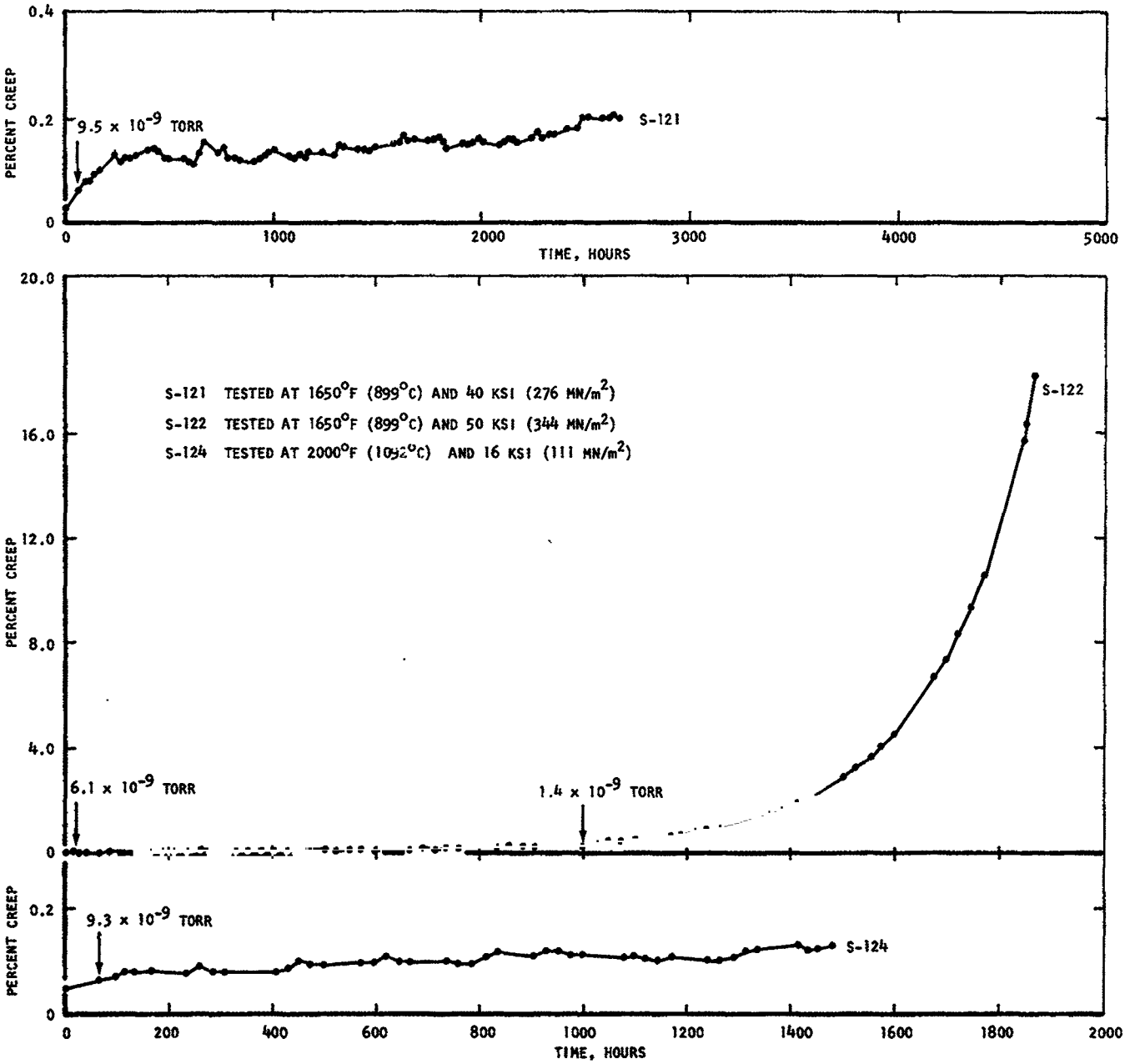

FIGURE III-4. CREEP TEST DATA, T-111 G.E. CORROSION LOOP EXPOSURE SPECIMENS. TEST NOS. S-121, S-122, AND S-124, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

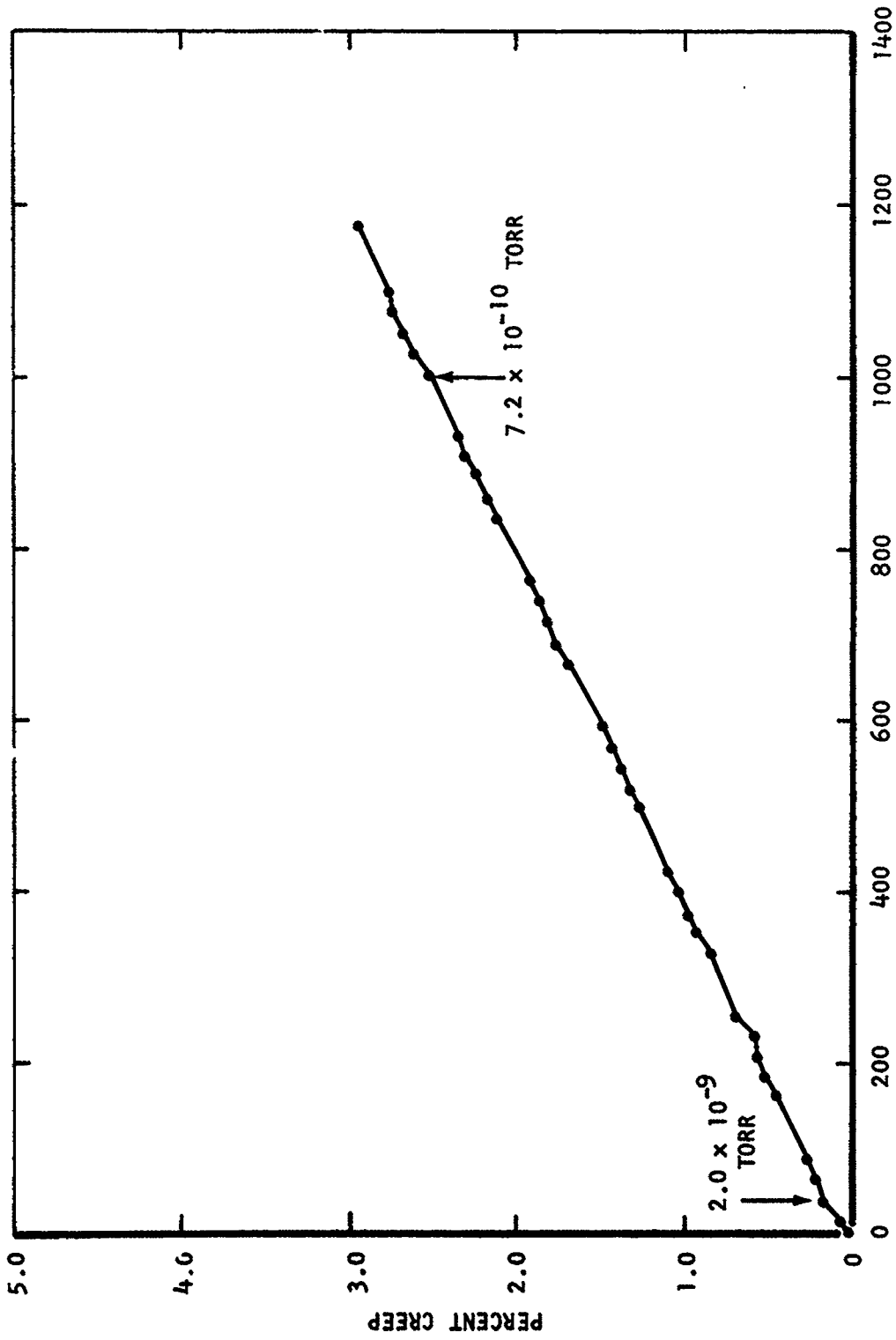

FIGURE III-5. CREEP TEST DATA, T-111 HEAT NO. 848001 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 1900°F (1038°C) AND 20 KSI (138 MN/m^2), TEST NO. S-107, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10-8 TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

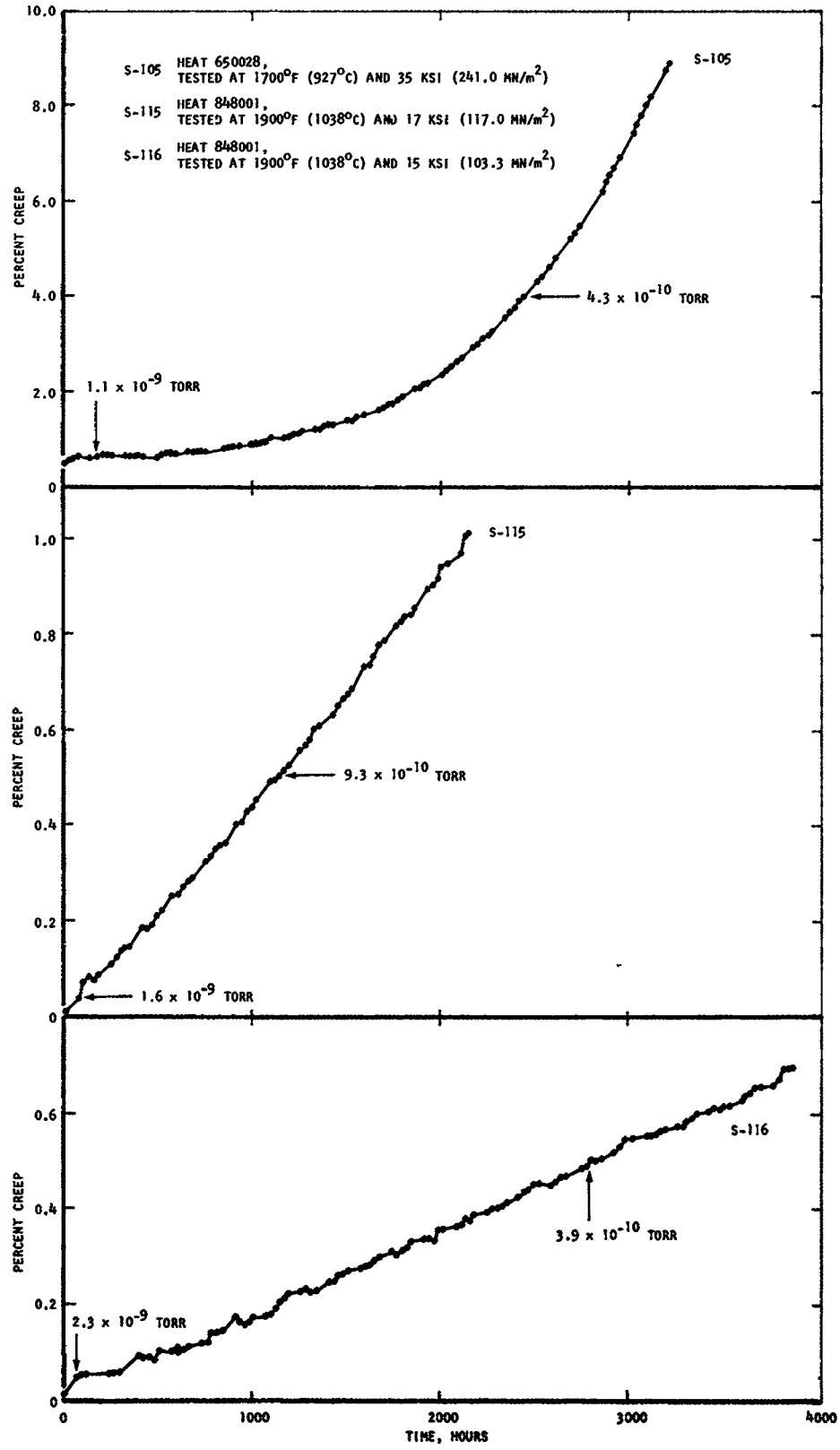

FIGURE III-6. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S-105, S-115, AND S-116, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

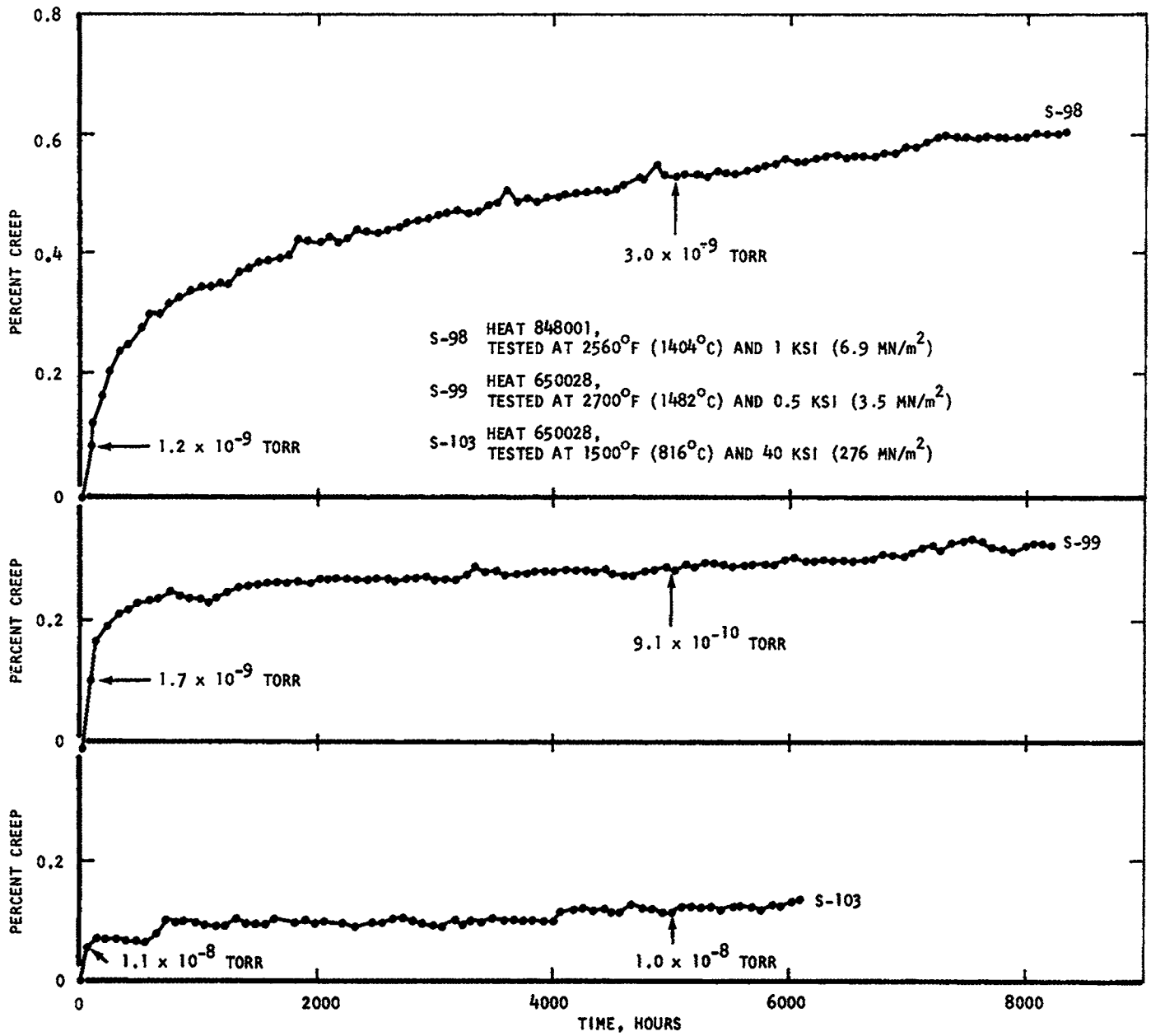

FIGURE III-7. CREEP TEST DATA, T-111 ANNEALED 1 HOUR AT 3000°F (1649°C), TEST NOS. S-98, S-99, AND S-103, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

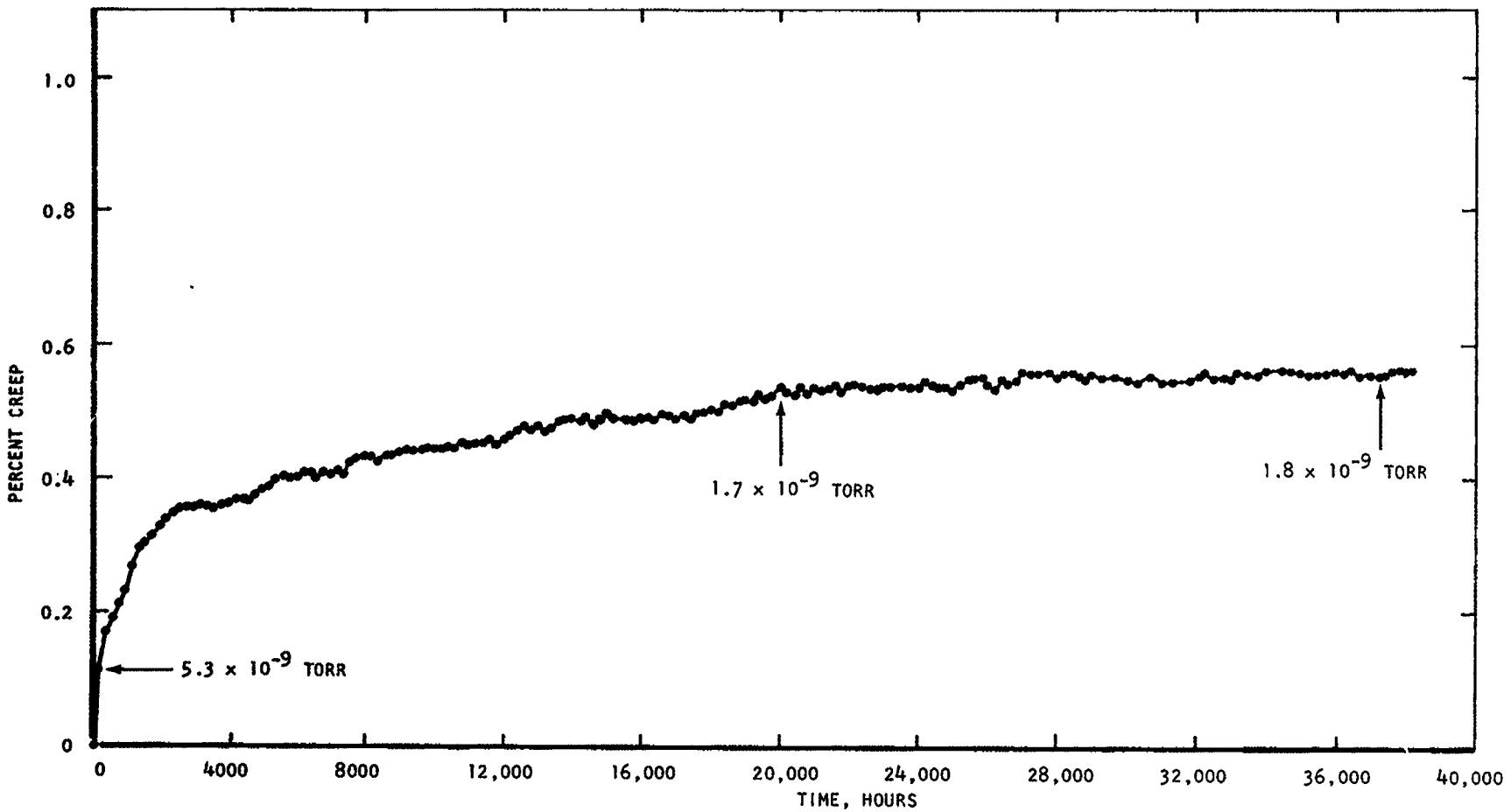

FIGURE III-8. CREEP TEST DATA, T-111 HEAT NO. D-1670 ANNEALED 1 HOUR AT 3000°F (1649°C), TESTED AT 2600°F (1427°C) AND 0.5 KSI (3.5 mN/m^2), TEST NO. S-28, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

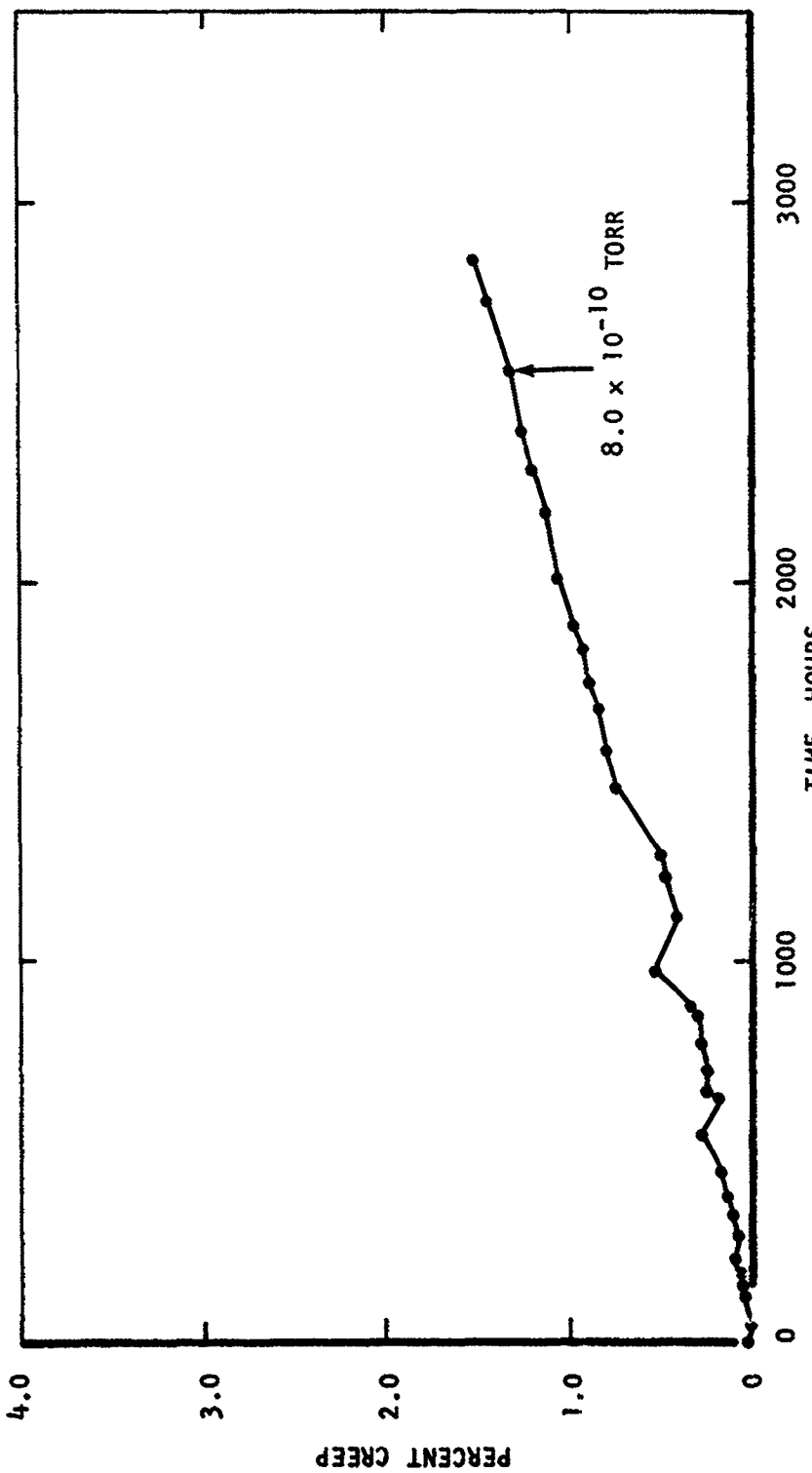

FIGURE III-9. CREEP TEST DATA, ASTAR 811C HEAT NO. NASV-20 FROM G.E. ALKALI METAL CORROSION LOOP EXPOSURE PROGRAM, TESTED AT 2400°F (1316°C) AND 8 KSI (55.1 mN/m2), TEST NO. S-108, TESTED AT A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVE INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

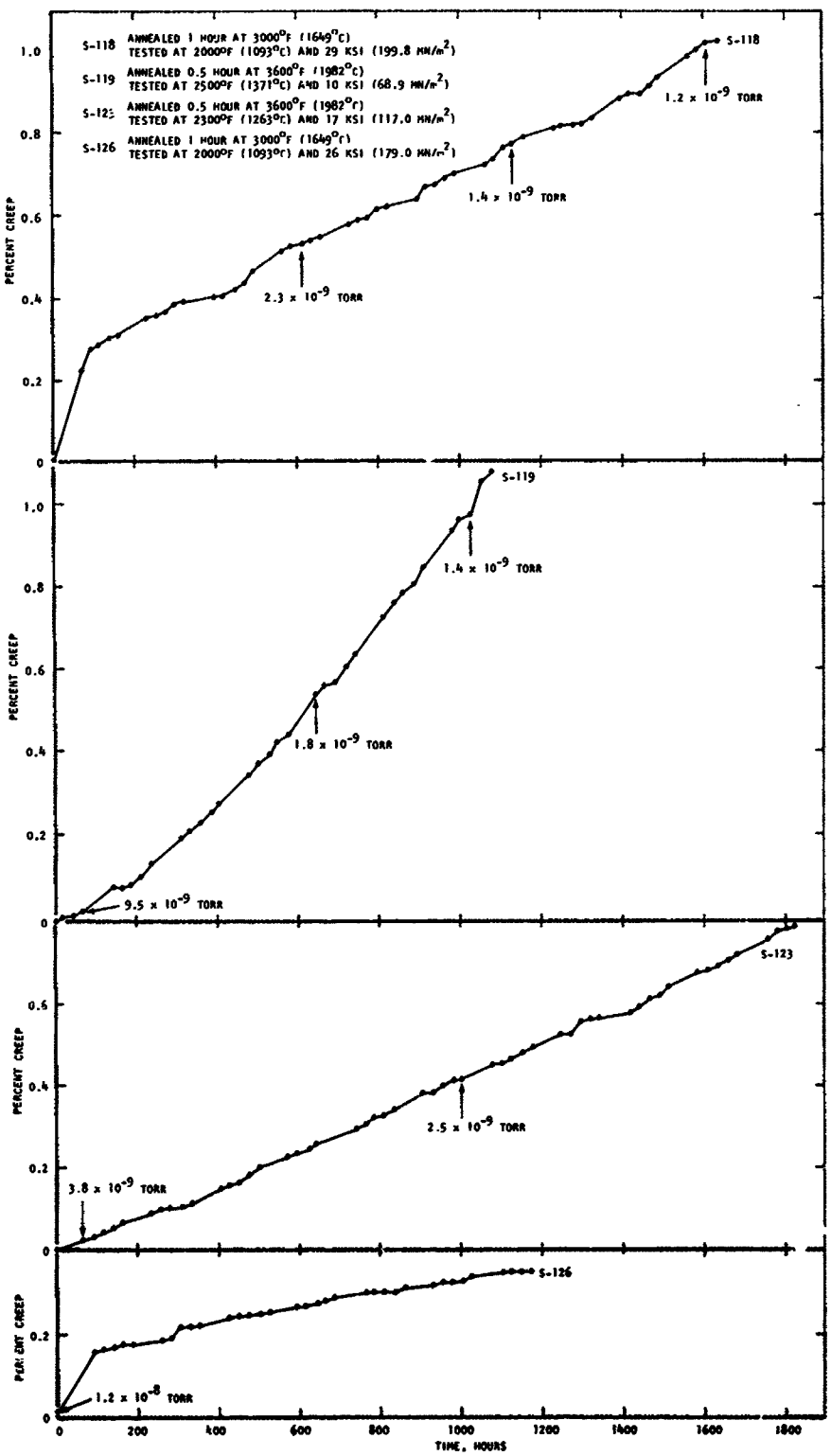

FIGURE III-10. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056, TEST NOS. S-118, S-119, S-123, AND S-126, TESTED IN A VACUUM ENVIRONMENT OF $<1 \times 10^{-8}$ TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

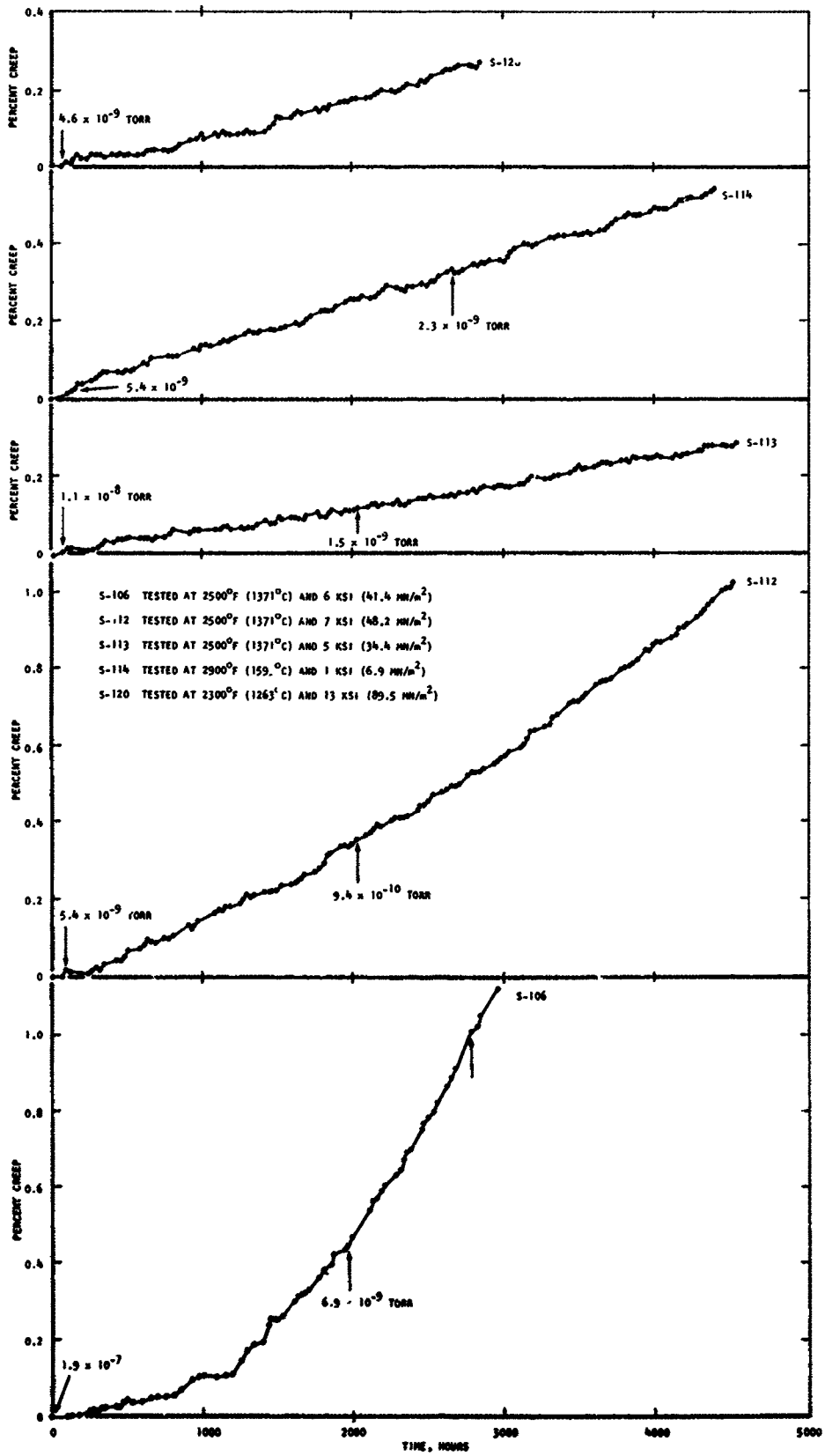

FIGURE III-11. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 0.5 HOUR AT 3600°F (1982°C), TEST NOS. S-106, S-112, S-113, S-114, AND S-120, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

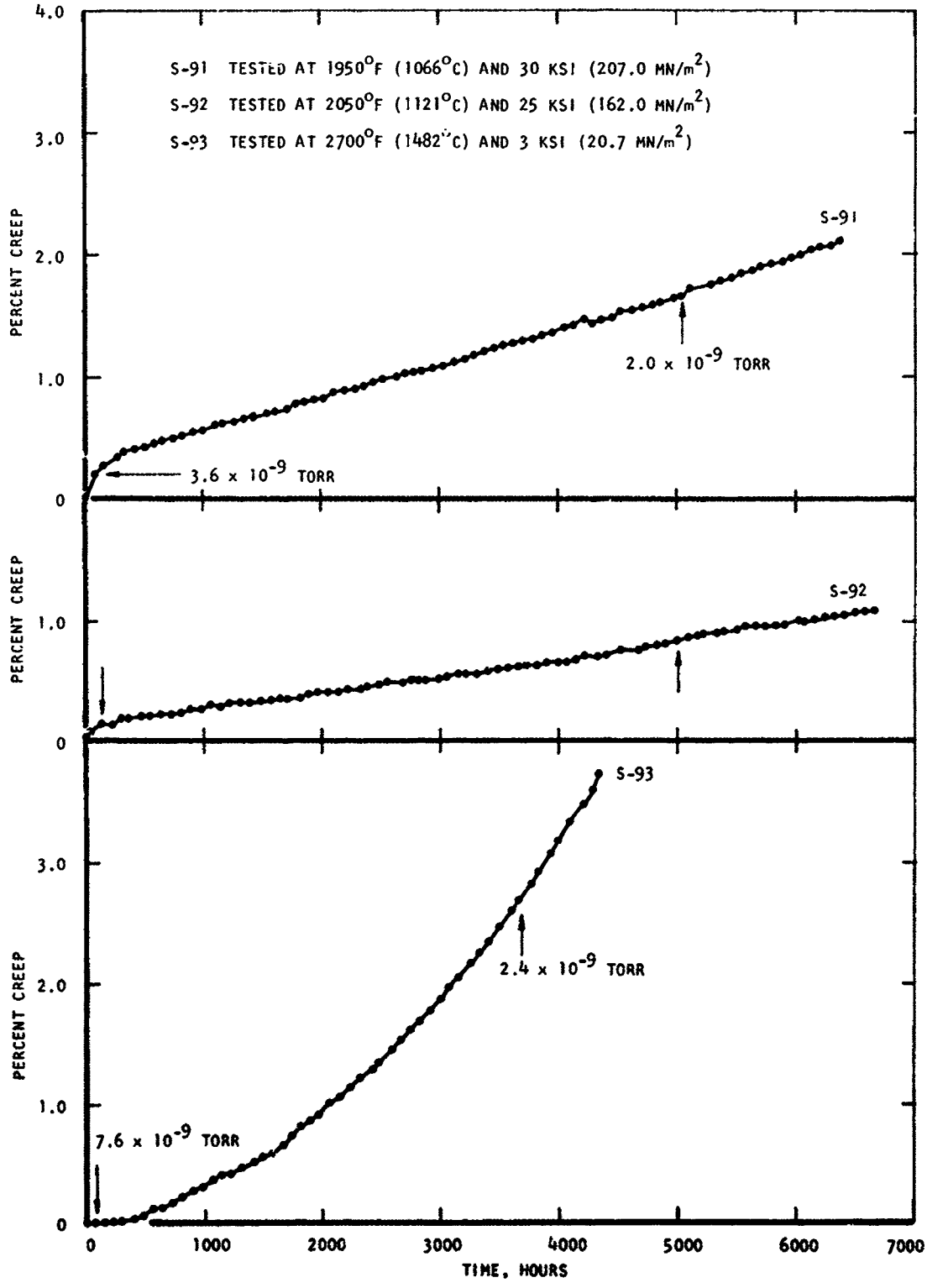

FIGURE III-12. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 0.5 HOUR AT 3600°F (1982°C), TEST NOS. S-91, S-92, AND S-93, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.

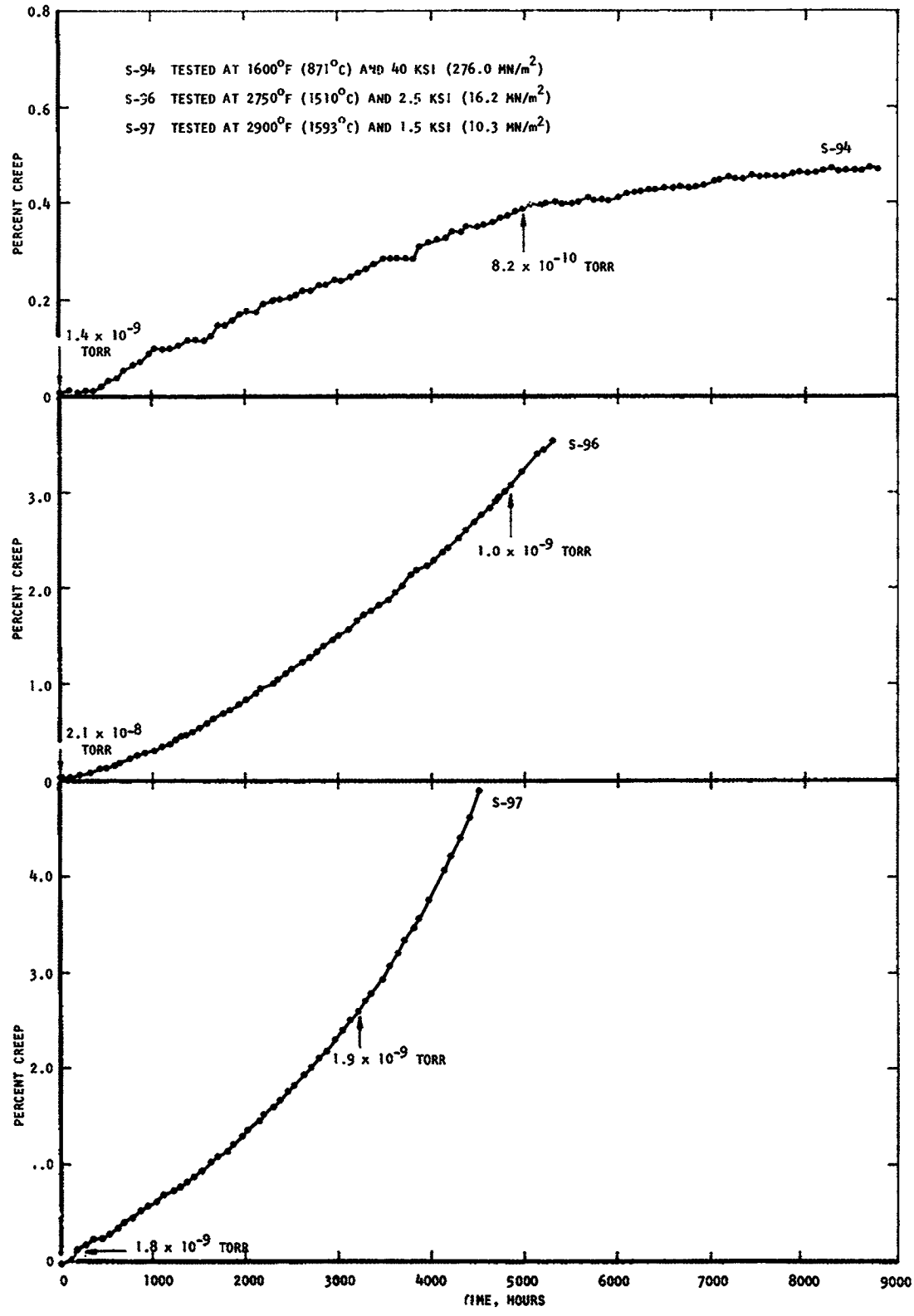

FIGURE III-13. CREEP TEST DATA, ASTAR 811C HEAT NO. 650056 ANNEALED 0.5 HOUR AT 3600°F (1982°C), TEST NOS. S-94, S-96, AND S-97, TESTED IN A VACUUM ENVIRONMENT OF <1 x 10^{-8} TORR. ARROWS ON THE CURVES INDICATE CHAMBER PRESSURE AT VARIOUS INTERVALS DURING THE TEST.